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Regular Publications

The Society issues annually, in four quarterly parts, a single serial octavo publication entitled Bulletin of the Geological Society of America, the edition being 700 copies. A small supply of authors' separates of the longer articles is kept for sale by the Secretary at the prices quoted in each volume.

The Bulletin is sold at the uniform price of ten dollars ($10.00) per volume, with a discount of twenty-five (25) per cent to Fellows of the Society. persons residing elsewhere than in North America, and public and institutional libraries; carriage extra. Subscriptions are payable in advance. Regular subscribers within the United States of America and its possessions receive their parts, postage paid, as issued. Forty (40) cents per volume must be added to the subscription price to cover postage to other countries in the Postal Union.

The price of the index to volumes 1-10 is $2.25 and of the index to volumes 11-20 is $3.50; carriage extra. No reduction is made to dealers. Orders should be addressed to the Secretary, whose address is care of the American Museum of Natural History, New York, N. Y., and drafts and money orders should be made payable to *The Geological Society of America.*

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Vol. 3, 1891	541 + xi	17	72
Vol. 4, 1892	458 + xi	10	55
Vol. 5, 1893	655 + xii	21	43
Vol. 6, 1894	528 + x	27	40
Vol. 7, 1895	558 + x	24	61
Vol. 8, 1896	446 + x	51	29
Vol. 9, 1897	460 + x	29	49
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Vol. 12, 1900	538 + xii	45	28
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Vol. 20, 1908	749 + xiv	111	35
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Vol. 22, 1910	747 + xii	31	66
Vol. 23, 1911	758 + xvi	43	44
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Vol. 25, 1913	802 + xviii	28	47
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Proceedings of the Eighth Annual Meeting of the Paleontological Society, held at Albany, New York, December 27, 28, and 29, 1916. R. S. Bassler, *Secretary* †	189–234	....	....	.55	.80
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Second report of the Committee on the Nomenclature of the Cranial Elements in the Permian Tetrapoda. W. K. Gregory, *Secretary of the Committee*, with Appendices by R. Broom, D. M. S. Watson, and S. W. Williston †	973–986	....	....	.15	.25

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Irregular Publications

In the interest of exact bibliography, the Society takes cognizance of all publications issued wholly or in part under its auspices. Each author of a memoir receives 30 copies without cost, and is permitted to order any additional number at a slight advance on cost of paper and presswork; and these reprints are identical with those of the editions issued and distributed by the Society; but the cover bears only the title of the paper, the author's name, and the statement [Reprinted from the Bulletin of the Geological Society of America, vol. —, pp. —, pl. — (Date)]. Contributors to the Proceedings and "Abstracts of Papers" are also authorized to order any number of separate copies of their papers at a slight advance on cost of paper and presswork; but such separates are bibliographically distinct from the reprints issued by the Society.

The following separates of parts of volume 28 have been issued:

Regular Editions

Pages	235–248,			40	copies.	March	31, 1917.
"	249–278,	plates	6– 9,	540	"	"	31, 1917.
"	279–308,	"	10–11,	90	"	June	9, 1917.
"	309–322,	"	12–17,	40	"	"	9, 1917.
"	323–334,			40	"	"	11, 1917.
"	335–346,	"	18–20,	140	"	"	11, 1917.
"	347–350,	plate	21,	140	"	"	11, 1917.
"	351–374,			140	"	"	11, 1917.
"	375–418,			540	"	"	13, 1917.
"	419–430,			110	"	"	14, 1917.
"	431–450,	plates	22–28,	540	"	"	18, 1917.
"	451–462,			110	"	July	10, 1917.
"	463–500,			140	"	"	21, 1917.
"	501–514,	"	29–33,	115	"	September	21, 1917.
"	515–542,	"	34–35,	60	"	"	21, 1917.
"	543–552,	"	36–42,	340	"	"	21, 1917.
"	553–602,			1,040	"	"	30, 1917.
"	603–616,			540	"	"	30, 1917.
"	617–654,			40	"	"	30, 1917.
"	655–666,			60	"	"	30, 1917.
"	667–676,			40	"	"	30, 1917.
"	677–684,			240	"	"	30, 1917.
"	685–720,			540	"	"	21, 1917.
"	721–726,			240	"	"	30, 1917.
"	727–734,			240	"	"	30, 1917.
"	735–744,			340	"	December	4, 1917.
"	745–904,	plates	43–46,	210	"	"	4, 1917.
"	905–916,			110	"	"	14, 1917.
"	917–924,			240	"	"	19, 1917.
"	925–932,			40	"	"	19, 1917.
"	933–944,	plates	47–48,	140	"	"	19, 1917.
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"	959–964,*†			515	"	"	19, 1917.
"	965–972,*†			215	"	"	19, 1917.
"	973–986,*†			415	"	"	19, 1917.

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[*] Bearing on the cover

PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY.

[Reprinted from the Bulletin of the Geological Society of America, vol. ——, pp. ——, pls. ——, (Date)].

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"	40– 67,	"	2,	240 "	"	31, 1917.
"	67– 70,	"	3,	100 "	"	31, 1917.
"	70– 80,	"	4,	140 "	"	31, 1917.
"	81–123,	"	5,	240 "	"	31, 1917.
"	177–188,			140 "	"	31, 1917.
"	189–234,			215 "	"	31, 1917.

CORRECTIONS AND INSERTIONS

Contributors to volume 28 have been invited to send corrections and insertions to be made in their papers, and the volume has been scanned with some care by the Editor. The following are such corrections and insertions as are deemed worthy of attention:

Page 207, line 12 from top; *for* "Perdue" *read* Purdue
" 256, line 24 from top; *for* "figure 8" *read* figure 6
" 332, line 6 from bottom; *for* "Lake Ontario" *read* Lake Erie
" 728, line 13 from top; *for* "inorganic" *read* organic

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‡ Bearing imprint [From Bull. Geol. Soc. Am., Vol. 28, 1916].

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
Vol. 28, pp. 1-188, pls. 1-5 March 31, 1917

PROCEEDINGS OF THE TWENTY-NINTH ANNUAL MEETING OF THE GEOLOGICAL SOCIETY OF AMERICA, HELD AT ALBANY, NEW YORK, DECEMBER 27, 28, AND 29, 1916.

DEC 27 1917
National

Charles P. Berkey, *Secretary pro tem.*

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SESSION OF WEDNESDAY, DECEMBER 27

The first general session of the Society was called to order at 9.45 o'clock a. m., Wednesday, December 27, in the Auditorium of the State Museum Building, Albany, New York, by President John M. Clarke. A brief introductory welcome was given by the President, followed by an outline of the conditions and surroundings in which the Society finds itself at this annual meeting.

CONTRIBUTION TO HOVEY RELIEF EXPEDITION

A letter was read from Dr. E. O. Hovey, Secretary of the Society. The only additional information available, received late in December, indicates that Doctor Hovey is still ice-bound at Parkers Snow Bay, in Greenland, and it is certain that he can not return to America before the summer of 1917. The President, on behalf of the Council, announced that the Society had made a contribution toward the relief expedition which was sent into the Arctic during the past summer, and that arrangements were as complete as could be made for the safe return of the expedition.

The report of the Council for the year ending November 30, 1916, was presented as follows:

REPORT OF THE COUNCIL

To the Geological Society of America, in twenty-ninth annual meeting assembled:

The regular annual meeting of the Council was held at Washington, District of Columbia, in connection with the meeting of the Society, December 28-30, 1915.

The details of administration for the twenty-eighth year of the existence of the Society are given in the following reports of officers:

Secretary's Report

To the Council of the Geological Society of America:

Meetings.—The proceedings of the annual general meeting of the Society, held at Washington, District of Columbia, December 28-30, 1915, have been recorded in volume 27, pages 1-138, and of the Paleontological Society, pages 139-174, of the Bulletin.

Membership.—During the past year the Society has lost five Fellows by death—Charles A. Davis, C. Willard Hayes, Frank A. Hill, F. J. H. Merrill, and Charles S. Prosser. Two resignations have become effective. The names of the six Fellows elected at the Washington meeting have been added to the list, all of them having completed their membership according to the rule. The present enrollment of the Society is 375. Twenty-nine candidates are before the Society for election and several applications are under consideration by the Council.

Distribution of Bulletin.—There have been received during the year 8 new subscriptions to the Bulletin, and 5 subscriptions have been discontinued, making the number of subscribers 118.

The irregular distribution of the Bulletin during the past year has been as follows: Complete volumes sold to the public, 32; sold to Fellows, 1; sent out to supply deficiencies, 1, and delinquents, 11; brochures sent out to supply deficiencies, 6, and delinquents, 103; sold to Fellows, 8; sold to the public, 48.

Bulletin sales.—The receipts from subscriptions to and sales of the Bulletin during the past year are shown in the following table:

Bulletin Receipts, December 1, 1915–November 30, 1916

	Complete volumes.			Brochures.			Grand total.
	Fellows.	Public.	Total.	Fellows.	Public.	Total.	
Volume 1							
Volume 2		$7.50	$7.50				$7.50
Volume 3		7.50	7.50				7.50
Volume 4		7.50	7.50				7.50
Volume 5		7.50	7.50				7.50
Volume 6					$1.00	$1.00	1.00
Volume 7		7.50	7.50				7.50
Volume 8					.75	.75	.75
Volume 9					.30	.30	.30
Volume 10					4.30	4.30	4.30
Volume 11					1.00	1.00	1.00
Volume 12							
Volume 13		7.50	7.50				7.50
Volume 14							
Volume 15					.55	.55	.55
Volume 16							
Volume 17							
Volume 18					1.55	1.55	1.55
Volume 19							
Volume 20		7.50	7.50				7.50
Volume 21		7.50	7.50		.90	.90	8.40
Volume 22		15.00	15.00				15.00
Volume 23		22.50	22.50		6.80	6.80	29.30
Volume 24		30.00	30.00	$9.15	11.65	20.80	50.80
Volume 25		37.50	37.50	7.25	14.85	22.10	59.60
Volume 26	$7.50	62.50	70.00	2.25	11.60	13.85	83.85
Volume 27		845.00	845.00		.15	.15	845.15
Volume 28		75.00	75.00				75.00
Total	$7.50	$1,147.50	$1,155.00	$18.65	$55.40	$74.05	$1,229.05
Index 1–10		2.25	2.25				2.25
Index 11–20							
Total	$7.50	$1,149.75	$1,157.25	$18.65	$55.40	$74.05	$1,231.30

Receipts for the fiscal year		$1,231.30
Previously reported		19,378.89
Total receipts to date		$20,610.19
Charged, but not yet received:	On 1911 account	7.50
	On 1916 account	15.15
Total sales to date		$20,632.84

Expenses.—The following table gives the cost of administration and of Bulletin distribution during the past year:

EXPENDITURES OF SECRETARY'S OFFICE DURING THE FISCAL YEAR ENDING NOVEMBER 30, 1916.

Account of Administration

Printing (including annual meetings of 1915 and 1916)	$202.89	
Postage	46.73	
Telephone charges	9.02	
Note book	.65	
Messenger service	.75	
Car fare	1.90	
Telegrams	4.17	
Post-cards	9.00	
Express charges	3.44	
Incidentals in connection with annual meeting	1.00	
Exchange on checks	.85	
Binding three copies of Bulletin	6.75	
Expenses of California meeting, 1915	94.24	
Total		$381.39

Account of Bulletin

Express and freight charges	$21.04	
Postage	6.72	
Collection charges on checks	1.21	
Telegrams	1.42	
Notary fee	.25	
Car fare	.10	
Total		30.74
		$412.13

Respectfully submitted,

CHARLES P. BERKEY,
Secretary pro tem.

TREASURER'S REPORT

To the Council of the Geological Society of America:

The Treasurer herewith submits his annual report for the year ending November 30, 1916.

The membership of the Society at the present time is 375, of whom 283 pay annual dues. Six new members were elected at the last annual meeting, all of whom qualified. There have been 5 deaths during the year and 2 resignations. Eighteen members are delinquent in the payment of dues—1 for 7 years, 2 for 5 years, 2 for 3 years, 6 for 2 years, and are therefore liable to be dropped from the roll—and 7 for 1 year.

The Treasurer bought during the year one Chicago Railways Company first mortgage five per cent bond, with interest, at a cost of $993.89. One bond of the New England Telephone and Telegraph Company was redeemed on April 1.

RECEIPTS

Balance in treasury December 1, 1915		$123.62	
Fellowship fees, 1914 (1)	$10.00		
1915 (11)	110.00		
1916 (267)	2,670.00		
1917 (1)	10.00		
		2,800.00	
Initiation fees (6)		60.00	
Interest on investments:			
Iowa Apartment House stock	$50.00		
Ontario Apartment House stock	200.00		
Texas & Pacific Railroad Company bonds	100.00		
U. S. Steel Corporation bonds	150.00		
St. Louis and San Francisco Railroad Company bond	50.00		
Fairmont & Clarksburg Traction Company bonds	100.00		
Consolidation Coal Company bonds	100.00		
Chicago Railways Company bonds	100.00		
Southern Bell Telephone and Telegraph Company bonds	100.00		
New England Telephone and Telegraph Company bond	25.00		
American Agricultural Chemical Company bonds	100.00		
Interest on deposits, Baltimore Trust Company	50.90		
		1,125.90	
Case Library, accessions for 1915		150.00 *	
Redemption of New England Telephone and Telegraph bond		1,000.00	
Collection charges added to checks		.70	
Received from Secretary:			
Sales of publications	$1,231.30		
Author's separates	56.10		
Author's corrections	6.85		
Collection charges added to checks	.38		
Binding	2.25		
Postage	8.79		
		1,305.68	
			$6,565.90

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* Received subsequent to bank balance.

EXPENDITURES

Secretary's office:		
Administration	$381.39	
Bulletin	30.74	
Salary	1,000.00	
		$1,412.13
Treasurer's office:		
Postage, bond, safe-deposit box, etc	$43.50	
Clerk	100.00	
Collection charges on checks	.20	
		143.70
Publication of Bulletin:		
Printing and paper	$2,279.24	
Engraving	239.48	
Editor's allowance	250.00	
		2,768.72
Purchase of one Chicago Railways Company five per cent bond, with interest	993.89	
Contribution to Crocker Land Expedition for Hovey relief ship	1,000.00	
Balance in Baltimore Trust Company December 1, 1916	97.46	
Check of Case Library deposited subsequent to bank balance	150.00	
		$6,565.90

Respectfully submitted,

Wm. Bullock Clark,
Treasurer.

Editor's Report

To the Council of the Geological Society of America:

The Editor submits herewith his annual report. The following tables cover statistical data for the twenty-seven volumes thus far issued:

ANALYSIS OF COSTS OF PUBLICATION

Cost.	Average—Vols. 1-25.	Vol. 26.	Vol. 27.
	pp. 759. pls. 42.	pp. 525. pls. 27.	pp. 757. pls. 30.
Letter press	$1,807.41	$1,076.22	$1,684.67
Illustrations	327.04	171.69	378.30
Total	$2,134.45	$1,248.01	$2,062.97
Average per page	$2.83	$2.37	$2.73

CLASSIFICATION OF SUBJECT-MATTER

Volume.	Areal geology.	Physical geology.	Glacial geology.	Physiographic geology.	Petrographic geology.	Stratigraphic geology.	Paleontologic geology.	Economic geology.	Official matter.	Memorials.	Unclassified.	Total.
	Number of pages.											
1......	116	137	92	18	83	44	47	.....	60	4	4	593+xii
2......	56	110	60	111	52	168	47	9	55	1	7	662+xiv
3......	56	41	44	41	32	158	104	.....	61	15	1	541+xii
4......	25	134	38	74	52	52	14	.....	47	32	2	458+xii
5......	138	135	70	54	28	51	107	.....	71	14	9	665+xii
6......	50	111	75	39	71	99	1	.....	63	25	4	538+x
7......	38	77	105	53	40	21	123	4	66	28	13	558+x
8......	34	50	98	5	43	67	58	14	79	8	....	446+x
9......	2	102	138	.....	44	28	64	16	64	12	....	460+x
10......	35	33	96	37	59	62	68	28	84	27	17	534+xiii
11......	65	110	21	10	54	31	188	7	71	60	46	651+xii
12......	199	39	55	53	24	98	5	5	70	2	....	538+xi
13......	125	17	13	24	28	116	42	4	165	32	29	583+xii
14......	48	47	48	59	183	118	22	1	80	14	1	609+xi
15......	26	124	3	94	36	267	.....	.....	77	17	3	636+x
16......	64	111	78	30	102	141	19	.....	67	22	15	636+xiii
17......	49	161	41	84	47	294	27	.....	71	9	2	785+xiv
18......	16	164	141	5	29	246	5	.....	68	40	3	717+xii
19......	106	108	29	66	30	155	32	....	56	15	20	617+x
20......	43	54	35	29	37	45	303	8	60	3	132	749+xiv
21......	72	234	75	48	85	70	106	1	111	11	10	823+xvi
22......	23	54	28	28	23	403	74	.....	63	49	1	747+xii
23......	75	52	126	108	19	145	134	.....	66	32	1	758+xvi
24......	18	57	96	57	49	160	106	23	133	53	3	737+xviii
25......	34	211	54	32	156	9	175	.....	108	9	22	802+xviii
26......	.....	72	23	11	56	90	148	.....	54	44	6	504+xxi
27......	1	59	125	31	146	20	271	2	73	24	5	739+xviii

Respectfully submitted,

JOSEPH STANLEY-BROWN, *Editor.*

The foregoing report is respectfully submitted,

THE COUNCIL.

December 27, 1916.

The report was laid on the table as usual until the following day.

ELECTION OF AUDITING COMMITTEE

An Auditing Committee, consisting of I. C. White, H. B. Kümmel, and Alfred H. Brooks, was then elected, and the Treasurer's report was referred to this committee for examination.

ELECTION OF OFFICERS

The Secretary declared the vote for officers for 1917 as follows, the ballots having been canvassed and counted by the Council in accordance with the By-Laws:

President:

Frank D. Adams, Montreal, Canada.

First Vice-President:

Andrew C. Lawson, Berkeley, California.

Second Vice-President:

W. D. Matthew, New York City.

Third Vice-President:

J. C. Merriam, Berkeley, California.

Secretary:

Edmund Otis Hovey, New York City.

Treasurer:

William Bullock Clark, Baltimore, Maryland.

Editor:

Joseph Stanley-Brown, New York City.

Librarian:

Frank R. Van Horn, Cleveland, Ohio.

Councilors:

Arthur L. Day, Washington, D. C.
William Harvey Emmons, Minneapolis, Minnesota.

ELECTION OF FELLOWS

The Secretary announced the election in due form of the following Fellows, the ballots having been canvassed and counted by the Council:

Alan Mara Bateman, Yale University, New Haven, Connecticut.
Charles F. Bowen, United States Geological Survey, Washington, D. C.
Edward Moore Jackson Burwash, University of Toronto, Toronto, Canada.
D. Dale Condit, United States Geological Survey, Washington, D. C.
Ralph Dixon Crawford, University of Colorado, Boulder, Colorado.

Alexander Deussen, University of Texas, Austin, Texas.
Charles Wales Drysdale, Geological Survey of Canada, Ottawa, Canada.
Marcus Isaac Goldman, United States Geological Survey, Washington, D. C.
Donnel Foster Hewett, United States Geological Survey, Washington, D. C.
Jesse Earl Hyde, Western Reserve University, Cleveland, Ohio.
William Alfred Johnston, Geological Survey of Canada, Ottawa, Canada.
Gerald Francis Loughlin, United States Geological Survey, Washington, D. C.
Charles T. Lupton, Cosden Oil and Gas Company, Tulsa, Oklahoma.
Warren Judson Mead, University of Wisconsin, Madison, Wisconsin.
Oscar E. Meinzer, United States Geological Survey, Washington, D. C.
Hugh D. Miser, United States Geological Survey, Washington, D. C.
Levi F. Noble, Valyermo, California.
Robert W. Pack, United States Geological Survey, Washington, D. C.
William Armstrong Price, Jr., West Virginia University, Morgantown, West Virginia.
Leopold Reinecke, Geological Survey of Canada, Ottawa, Canada.
Henry Hollister Robinson, Peabody Museum, New Haven, Connecticut.
Bruce Rose, Geological Survey of Canada, Ottawa, Canada.
Reno H. Sales, Anaconda Copper Mining Company, Butte, Montana.
Robert Speight, Christ Church, Canterbury College, New Zealand.
Eugene Stebinger, Jr., United States Geological Survey, Washington, D. C.
Edward Steidtmann, University of Wisconsin, Madison, Wisconsin.
Merton Yarwood Williams, Geological Survey of Canada, Ottawa, Canada.
Morley Evans Wilson, Geological Survey of Canada, Ottawa, Canada.
Victor Ziegler, Colorado School of Mines, Golden, Colorado.

NECROLOGY

Announcement was made by the Secretary that the Society had lost five Fellows by death during 1916: Charles A. Davis, C. Willard Hayes, E. W. Hilgard, Charles A. Prosser, and F. J. H. Merrill. One death of the preceding year, that of Frank A. Hill, was also included in the list, notice not having been received in time for the meeting of 1915.

The following memorials of deceased members were then presented:

MEMORIAL OF CHARLES A. DAVIS

BY ALFRED C. LANE

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EARLY LIFE

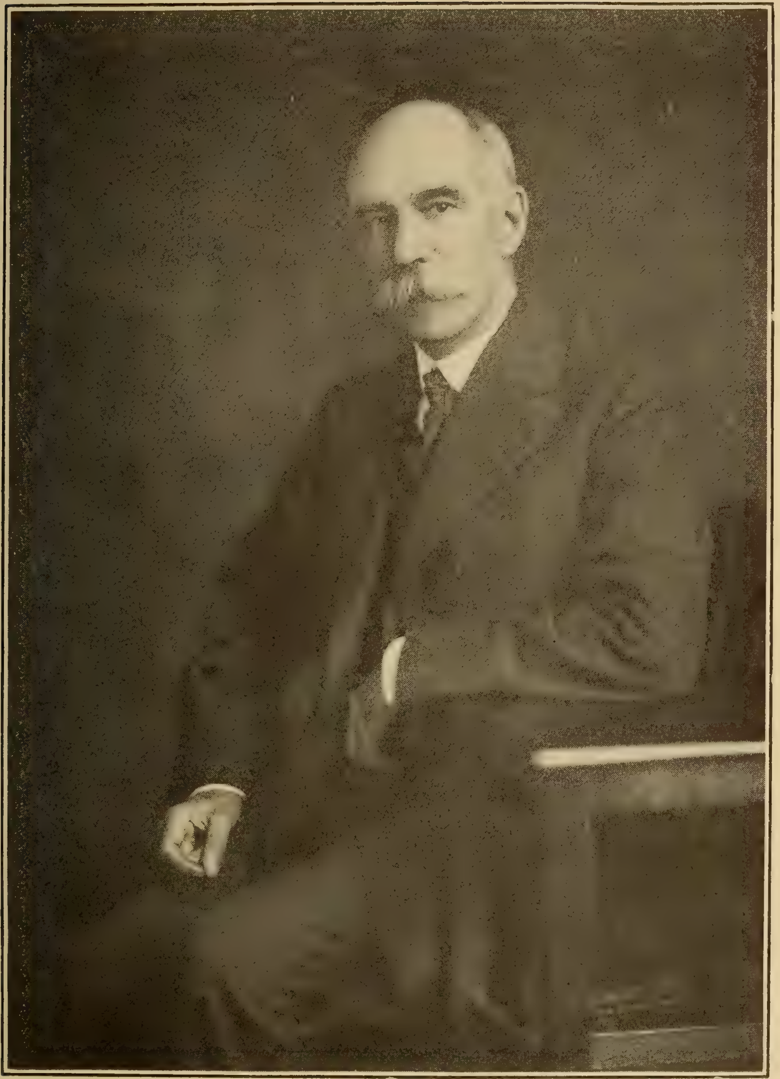
Geology is the record of how things came to be as they are, and so to me one of the most interesting things about any savant is how he came to be one.

Prof. Charles Albert Davis came into this life at Portsmouth, New Hampshire, on September 29, 1861, as the son of Lewis Gilman Davis and Frances Syrena Peirce, of old New England stock. His mother as a girl lived next door to Thomas Bailey Aldrich, in an old house in Portsmouth which had been a block-house, and used to ride on that "bad boy's" pony, "Gypsy." His father came from Durham, New Hampshire, and was a descendant of the family after which Gilmanton, New Hampshire, was named. His parents were both fond of outdoors and of long walks in the woods, and even after they were fifty years old used to take ten-mile tramps on Sundays to "rest them up."

His father had one of the show flower gardens of Portsmouth, and used to get up before 4 in the morning in order to cultivate it without neglecting his photographic business, which was one of the best in Portsmouth.

When Charles was only two years old his parents began to take the future scientist with them, and so his training in the recognition of plants and other objects started very early in life. By the time he was eight or nine years of age he was off on trips with boys, but he never was fond of hunting. On the first trip he made to hunt with a rifle, as he raised the weapon to aim a bird came and sat on the barrel. That exhibition of confidence disarmed him and he never went shooting thereafter. He was very fond of cats, and in Michigan some very intelligent Angoras were members of the family.

He went through the Portsmouth public schools, graduating from the high school when but sixteen. Then he worked three years in the photographic studio of his father, obtaining a knowledge of photography and chemicals of much use to him all his life. But the love of learning was



Chas. A. Davis.

fanned into flame by the principal of the Portsmouth High School, who, on her marriage to the principal of the Auburn High School, offered him a chance to go there and live with them, brush up his Greek, and enter Bowdoin College. This he did after a year, in 1882, at the age of twenty.

He largely worked his way through college, though he had one of the scholarships assigned to students who had no bad habits. He was a member of the Alpha Delta Phi and of Phi Beta Kappa fraternities, steward of a dining club, and also curator of the Cleveland Mineral Cabinet, which contained Haüry's famous collection. He thus gained a knowledge of mineralogy, which often surprised me in later life, long after his main work had gone in other directions. He sold bicycles, and was proud all his life of the fact that he was the first appointed consul of the League of American Wheelmen. No doubt his bicycling career was aided by that Yankee mechanical knack at tinkering—a strong trait—which made him an expert repairer of old mahogany furniture and a diviser of mechanical contrivances like his peat sampler. The cunning hand added to the artistic eye, inherited from his father, also made him good at water colors and in drawing, which was especially convenient in the preparation of illustrations.

While in Bowdoin he met Frances Margaret Humphreys, on whom he ever after lavished a devotion, a care, and an admiration which was its own great reward. She was also of old New England stock, and had the wide sympathy, brilliancy of conversation, and social intuition which not only make an ideal wife, but were qualities most helpful in the entertaining of undergraduates.

AT ALMA

He graduated at Bowdoin in 1886 (A. B.), married that summer, August 29, 1886, and went to the Hyde Park High School, in the suburbs of Chicago, Illinois. But though a good teacher, a big city was not his proper place, and in 1887 he gladly went to the college at Alma, near the center of lower Michigan, his remarkable breadth of scientific interest and training making him an exceptional teacher of natural science and chemistry in a small institution. In 1889 he took his A. M. from Bowdoin. In 1894 he assisted in organizing the Michigan Academy of Science and was its first secretary. Associated with him in this work were Sherzer, Jefferson, Russell, and other well known men.

Learning that Professor Davis had preserved the drillings of the then remarkably deep well of the Alma Sanitarium, I went to Alma to study them, and thus met him for the first time. An atmosphere of plain living (tempered by a delicious sauce of mushrooms that he gathered on the college campus) and high thinking surrounded his home. His Alma students in various parts of the State spoke highly of him. He was a pillar of the local Presbyterian Church, and while as quiet and reserved in the expression of his religious life as in the expression of other emotions, the student who asked him whether a scientist could be a Christian was but drawing him out. Truly might his wife reply, when asked whether he ever preached, that he was too busy practising.

In these years at Alma he became well acquainted with the plants and animals of the region. While primarily a botanist, little that was unusual escaped his eye. On a casual visit to the Huron Mountain Club, he collected a form of fresh-water shell which had been sought by the best specialists and had before been known only by five specimens, and he was already getting the familiarity with the "marl" lakes which later led to his first noteworthy geological discovery.

The following extracts from letters illustrate his life and scientific interests at Alma:[1]

Just after Thanksgiving, 1897, he writes:

> "Until Tuesday I shall be busy getting ready for a talk on birds before the Woman's Club, which is to have a bird day, with me as chief attraction, not as a bird, but as a sort of special pleader for them."

> "ALMA, MICHIGAN, *March* 21, 1898.
>
> "I am unable to find my notes on the analyses of the Sanitarium well which I made some years ago, but the results were printed on a card of which you may have a copy. The total solids—the Ca and Mg and Na salts—were correctly determined except the NaI and NaBr, those being set down in the list by the head physician of that day, who did it without my knowledge. He got my report of progress and filled out the analysis to suit his ideas of what should be present."

Naturally, as the Michigan Geological Survey resumed work in the Lower Peninsula, in 1896-1898, he was drafted into service. He was also of the greatest help in planning that first systematic qualitative field testing of well waters, which proved to be very useful in locating the Michigan Series and which was so developed by the United States Geological Survey. His work found expression in the reports on Sanilac, Huron, and Tuscola counties, the latter being almost wholly his own work. The contour map of Tuscola County from barometric data was remarkably expressive.

In all this work, and indeed during all his scientific life, he was interested in geology, as well as the plants and animals which came under his observation, as letters to Bryant Walker on the fresh-water shells show:

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[1] Unless specified, from letters to A. C. Lane. I have tried to give extracts from one letter each year after 1897, thus showing where he was and what his chief scientific interests were that year.

"ANN ARBOR, MICHIGAN, *November* 3, 1905.

"After the first big falls in the Menominee [River], those from which I sent the specimens to you, the Unionidæ were less numerous in species and individuals, all the larger ones seeming to stop below the falls. This I think will be shown by the material which I have for you. The land shells I did not have favorable opportunity to look for, and moreover fire has run over so much of the country that I expect many species are scarce or exterminated altogether. I was interested to find *Patula alternata* a common species on and among the talus slabs on several outcrops which I visited. Among the things which I thought were of special interest were two fairly good specimens of a big thick-shelled Unio which I found on the beach of the sandy and pebbly shore of Lake Superior between White Fish Point and Grand Marais—a long distance from the mouth of any stream.

"Yours very truly, CHAS. A. DAVIS."

In presenting "A list of shells from the east coast of Florida," in the Nautilus, Bryant Walker writes:

"The late Dr. Charles A. Davis, the well known peat expert of the United States Bureau of Mines, in addition to his special acquirements in geology and botany, was a good all-round zoologist, and had a lively and unaffected interest in the work that any of his friends might be carrying on in that department. It was his kindly habit in his travels about the country to preserve any specimens that he came across that seemed to him likely to be of interest to any of his zoological friends. It will be remembered that the conchologists owe to him the rediscovery of the long lost *Planorbis multivolvis* Case (Nautilus, volume xxi, page 61), and also the little *Lymnæa davisi* Walker (Nautilus, volume xxii, page 17), which bears his name."

In the spring of 1911 Doctor Davis' professional duties took him to Florida, and while there he collected quite a number of samples of "drift," which in due time came into my possession.

His interest in ecologic botany is brought out in his correspondence with C. K. Dodge, taken from two letters—one from the beginning, the other showing his interest even when death was near. Mr. Dodge writes from Port Huron, Michigan, under date of January 16, 1917, and quotes the following sentences indicating Professor Davis' ways of working:

"What you do, do in a systematic way."

"Keep specimens and take notes. Let us know what you are doing. Give us also the benefit of your work."

"We know after all very little about the wild plants of Michigan. Do your work in a systematic way. We want to know what we have."

"Beginning at the south line of the State, follow up carefully the divide between the two big lakes to Mackinac City. *You will have plenty to do as long as you live.*"

This must have been one of his last long letters:

"WASHINGTON, D. C., *February* 11, 1916.

"MY DEAR MR. DODGE: I owe you an apology for not writing you before, and I will explain rather than apologize. Just before Thanksgiving, when I was settling down to work in a new home, for we had moved in October, Mrs. Davis was taken seriously and very painfully sick with general neuritis and has been in bed ever since, most of the time with a nurse. She was delirious a good deal of the time for some weeks, and I have spent my evenings and Sundays in relieving the nurse and in doing what I could to make Mrs. Davis more comfortable, which at best was not very much. However, she is now considerably better, is having much less pain, and tonight I am taking time to write to you while she is asleep, the first time for a long time when she has been able to sleep so early in the evening. This explains why I have not been a better correspondent.

"I want also to explain why I did not see you when I went to Michigan in the fall. I was late in getting away on the trip West and only spent a week in all away from Washington. My main object in going was to attend a meeting of the American Peat Society in Detroit, and while there I stopped with Bryant Walker, who told me that you were at that time on your trip in the Upper Peninsula; hence I did not go to Port Huron. If you had been at home I should have spent Sunday at least with you and probably longer.

"On your last trip to the Upper Peninsula you covered something of the same ground I did in 1905 with Leverett. We walked from Newberry to the mouth of the Two-hearted River, then along the shore to Grand Marais, taking three days to make the trip. The first night we stopped at the Half-way House, north of Newberry; the next at the Two-hearted River L. S. S., and the next at a fishing camp about half way between that and Grand Marais. It was a long and interesting walk. It was along the lake shore west of the Two-hearted River somewhere that I found *Empetrum nigrum* and a few other Northern plants; but most of the way *Pinus banksiana* and *Vaccinium canadense* were the striking plants, especially the latter, which that year bore a great crop of berries, which were ripe and fine, for we made the trip in September.

"Regarding *Quercus alba* in the Upper Peninsula, I saw it along the valley of the Menominee running up the river some distance, but just how far I am not sure now. *Quercus coccinea* grows over that way on the sand plains and as far east as the sand-plains south of Marquette and Ishpeming, if I remember correctly. The forests of the western end of the Upper Peninsula, after you get west of Marquette, in fact, are much heavier than those east of that point, except on the rock uplifts, the Huron and Porcupine Mountains, where the elevation and the shallow soils stunt the trees. But even on the shore of Lake Superior at Bessemer, or north of that town, the heavy, hardwood forest is strikingly different from the Jack and Norway pine forests on the great sand plains of the eastern end of the peninsula. The trees are large and thrifty and, except for the beech, are much the same as the forest you saw at Grand Island. Hard maple, birch (yellow and white), white elm, basswood, and some oaks, especially the red oak, are the common trees. The beech disappears rather suddenly in the Menominee Valley, not very far north of Lake Michigan, and its place is taken among the maples by yellow birch.

"Relative to the plants I collected on my last trip into that region, I have them here and am perfectly willing to send them to you as soon as I can pack them up. There are quite a lot of them and from a good many localities along the western end of the peninsula in the Menominee Valley, as well as in other places. I probably shall never make any use of them, and after you get them you can verify them and either incorporate them into your own collection or send them to the university, as you see fit. About the last time I ever saw our friend, Wheeler, he came up to my house and went over these plants and named them, or such as I had not named, and verified my names. I presume some of the names are still wrong, but you can get them straight. I have taken out a large series of Woodsias which I collected to have them worked over here by Doctor Maxon, of the National Herbarium, who expects sometime to monograph the genus. Any duplicates you find in these lots you may dispose of as you see fit.

"I hope I shall get time within a week or so to begin to send you these plants, but it will depend on how well Mrs. Davis keeps. There will be several good-sized bundles of them, and some of them are not in the older State lists from the Upper Peninsula, or at all, if I remember correctly.

With regard to a speech at the opening of the Hood Natural History Museum at Alma College, he writes, on October 9, 1899:

"I am, however, very greatly obliged to you for taking the opportunity to say what you outline, for it will be no end of a help to the cause in more ways than one, and will carry weight and have a force that anything which I might say, just a common barnyard servant of the college, could not possibly have.

"I am glad for that reason also that you have decided to say more than a few words. I think your 'orphan asylum for neglected idols' excellent and trust you will not forget to bring it in, for we have had a few lone and battered gods from the heathen world offered us already and, while something can undoubtedly be made of them in time, I wouldn't care for too many of them."

Vegetal Origin of Limestones

About 1897 cement factories in Michigan started up with a somewhat unhealthy growth, using various clays and an unconsolidated limestone that they called "shell marl," but which did not answer to the dictionary definition of marl, as it contained little or no clay; nor did it seem to be composed of comminuted shells.

Knowledge of its true production by means of the Charas or stoneworts, aided by algæ, was Davis' first great contribution to American geology. The vegetal origin of limestones, accepted almost at once and widely for these Pleistocene limestones, is only gradually winning its proper place as a key to the origin of many, and perhaps especially the Precambrian limestones. Davis was much pleased when Walcott took this view.

I. C. Russell, who had committed himself in favor of the chemical precipitation of these deposits, with characteristic candor and generosity accepted the results of Davis' work, got him to take the summer-school work at Ann Arbor in 1900 and 1901, had his company in the Upper Peninsula, and showed more affection than his habitually reserved, if not shy, nature often permitted. Davis had a way of winning affection.

The following letters from the files of the Michigan Geological Survey illustrate his first relations with Ann Arbor and the problem of the "marl":

(*Geological Survey Letters—Michigan*)[2]

"ALMA, MICHIGAN, *May* 28, 1900.

"I made a trip Saturday to Littlefield Lake, Gilmore township, Isabella County. It is a remarkable body of very fine marl, exceedingly white and fine, and of great extent. The lake is said to be about seven miles around, following the shoreline, and the exposed marl beach at low water would average from 12 to 20 feet wide around the entire lake, and runs from 22 to 35 feet deep in this entire area. Besides this exposed tract there are a number of large points covered with defunct cedar swamps, one of which has 33 and another about 40 acres in it, in which the average of about 20 holes gave 20½ feet as the depth. There are also three islands aggregating 10 acres in area of solid marl, which runs about 27 feet deep—more rather than less. There are several interesting features about the lake; but the most interesting one is the six daughter lakes formed by the development of marl points, which have gradually reached out and cut off the parts of the lake which lay between them. There are at least two of these lakelets in advanced stages of formation and the genesis of the older ones is very apparent. Another interesting thing is the fact that the marl islands are evidently built up on sand shoals about 30 feet below the surface,[3] for while the bottom was more than 40 feet deep off the islands we struck sand at about 30 feet on the edges of the islands and at about 27 or less in the middle. I did not have any sounding lines, so could not take measurement across the lake, but it was said to be above 60 feet deep between the larger island and the shore and more than 80 feet in the wider part. Another notable thing was the absence of any deep muck and of muck-forming vegetation. Another, the very steep slope of the marl; often the dip of the banks was apparently 80 or 85 degrees, and on the island near the foot of the lake the marl was washing across the submerged beach and drifting by the combined wave and current action, so that it made almost a perpendicular wall into deep water. Best of all, so far as my own work is concerned, the deposit is, beyond dispute, a plant-formed marl throughout. Chara is everywhere present and heavily incrusted, loaded in fact, and on the beach the 'sand' is broken fragments of that plant; the finer particles, where any structure is visible, are easily identified as the same substance. The other marl-building plant is the alga—a form related to Oscillaria, I think, which makes the nodules or concretions such as you found at Hamburg Junction. Here the more exposed and wave-washed shores are full of them; there are no other stones or pebbles on the entire lake. Shells of the usual lacustrine forms are fairly abundant, but of the more fragile types, and while they undoubtedly help form the deposit they are not the controlling factor or a very important one. I have undertaken to direct a survey of the lake and the marl and so shall go up again, and I hope you will go with me sometime. Steele has a set of instruments and is the man I am going to try for taking levels and plotting, if I can get him. I might add that the marl for some feet on top is of a distinctly granular type, but below is fine grained. I think that deposited in deeper water is the finer matter washed from the shores; that on top the coarser, sorted by wave and current action. I believe I can use this matter in my paper on vegetable origin of the marl to advantage."

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[2] I am obliged to my successor, R. C. Allen, for the use of letters from the Michigan Geological Survey files.

[3] I have seen a marl atoll that would have delighted Murray's heart.—A. C. L.

"ALMA, MICHIGAN, *August* 29, 1900.

"Got home last night and found, among other papers that had accumulated since my departure, a short paper which I got track of in Ann Arbor on 'Calcareous pebbles formed by algæ,' George Murray, London, 1895. It describes and figures the marl pebbles exactly and of course must be embodied in my paper, especially as the material came from a 'pond in Michigan.'"

"ALMA, MICHIGAN, *September* 1, 1900.

"I find the amount of Chara in Cedar Lake is simply immense. I counted from 50 to 80 tips of growing plants to the square centimeter—that is, the plants were simply so closely crowded that there was no chance for anything else to grow, and if my results of solid matter per plant are anywhere near average ones, as they certainly are, the amount of solid matter precipitated to the square centimeter of bottom is very considerable. The Schizothrix is also apparently abundant, but is not, so far as I could find, making pebbles at present at Cedar Lake, although the pebbles are common in the marl."

The way Professor Davis discovered calcium succinate in marl is shown in the following letters:

"ALMA, MICHIGAN, *December* 1, 1900.

"In looking over some marl analyses in which the CO_2 was determined separately, I notice that the CO_2 is deficient, if we assume that the Ca and Mg are all combined with CO_3 or with the other inorganic acid radicals present in the same analyses. It is probable, then, that some of the 'organic matter' is combined with the Ca in some way, as, for instance, as oxalate or tartrate or some other organic acid radical which does not yield CO_2 with dilute acids.

"I wish, if you have time, you would look over the marl analyses you have and see if the CO_2 would hold out for the Ca and Mg as carbonates—in those cases in which the CaO and MgO and CO_2 have been determined separately. If, in general, it is true that the CO_2 is deficient, then we have another step in the proof that the marl is a Chara, etcetera, product, especially if it can be demonstrated that the same compounds exist in the marl and in the plant."

"ALMA, MICHIGAN, *January* 28, 1901.

"Today I have made the first really satisfactory progress I have made in getting out the acid of the calcium organate, and the indications are so marked that I am going to follow them up to the limit. The acid in question is *succinic* acid and, as far as I was able to carry out the qualitative tests, the water extract of Chara gives marked and satisfactory reactions for every one of them sharply and promptly. It doesn't seem probable that this acid really is the one present; but if investigation shows that it really is, I do not see but what the probabilities will have to stand aside for actualities. I made up my mind, after trying other ways of working, that I would test for any organic acid I could find tests for that formed water soluble Ca salts, and, so far as I have tried these, succinic is the only one that gives good sharp tests and promptly reacts as soon as the reagent is applied; but I think it queer, nevertheless, that this should be the one. Please don't give this out until I have a chance to get more evidence to back me up; but so far as it goes the present evidence is good enough."

"ALMA, MICHIGAN, *August* 12, 1901.

"In his summary he says: (3) 'The deposition of the marl is caused by loss of CO_2 from subaqueous spring waters which bear the marl material into the lakes.' (4) 'That this loss of CO_2 is for the most part caused in three ways, viz: (*a*) By the increase in temperature of the incoming spring water. (*b*) By the decrease in pressure as the spring water rises to the surface. (*c*) By the action of different plants in abstracting CO_2 for food.'

"(*a*) seems probably fallacious, in that ground water is usually about 50°+ and would vary only slightly from that at the depth of the bottoms of the lakes mentioned, while the temperature of the bottoms of most of our lakes, and from the bottom up to somewhat near the surface, is below that figure—down to 39°, if I remember correctly. This, of course, if the spring were of large size, would cause a rapid rise of the spring water up to the surface—a spreading out and rapid precipitation of $CaCO_3$ if saturation were approached. The weak point in my knowledge seems to be exact and exhaustive knowledge of the composition of the waters of our morainal and clay springs and of the marl lakes. If saturation is not approached, the spring water is soon cooled off to a temperature lower than that which it has on coming from the ground and sinks, not rises, and becomes capable of taking more CO_2; hence no precipitation will occur. (I want material to back up this set of assertions. The Water Supply papers give me some help, but I would like enough material to make a good argument if I am going to work on this phase of the question at all.) I have rarely seen large springs from moraines, and if small springs run out on the sides of moraines, we only occasionally find tufa deposits about them and, I think I am safe in asserting, *only* when certain plants are present in the water; very frequently in Michigan it is certain species of moss. In case the $CaCO_3$ is precipitated by warming the water, every surface spring from clay moraines should be a mound spring, which is not true, as we know. In case a lake is fed by small springs, subaqueous, the water from these would be cooled before it had proceeded to the surface and no precipitation would be possible.

"(*b*) If the spring water rose to the surface, there would be a certain release of pressure, which would also permit release of CO_2, and, if the saturation point were reached, some precipitation. Again, we have to consider how great this pressure is, probably. Moraines 100 feet high above the level of lakes in their vicinity are rare in Michigan, so far as my observation goes. The ground water level does not often extend very high into even those which are more than 100 feet high. At Cedar Lake, I think, they said the flowing wells there had a head of about 20 feet, which is unusual for this region. Here at Alma the head of the wells with lowest outlets is about 20 feet; others with strong flows about 10 feet, etcetera. Assuming, however, that a spring has a head sufficiently high to make it break out in the bottom of a lake, it is not likely that the pressure upon it is very great when we get only an atmosphere pressure for 33° + feet of H_2O."

"ALMA, MICHIGAN, *August* 15, 1901.

"I have been meditating on the spring idea, and I think the fact that in teakettle scale, which is precipitated by release of CO_2 and raising the temperature, we always have the Fe thrown down and showing its presence by yellow stain is perhaps the best line of argument to show that marl is not due to these causes. In the same line of demonstration may be mentioned the fact that the precipitate that forms in the water from the flowing wells which come from glacial clays in this region, and which in some waters forms freely as the water stands and gets warmed up at the ordinary one-atmosphere pressure, is always well colored with Fe; in fact, give a distinct fulvous or even red stain to glassware and other forms of holders that are exposed to it. This precipitate is a mixture of Fe and $CaCO_3$; mainly the latter. But the Fe is always abundant enough to give a distinct color, while in marl it is only where springs run over the surface of the deposits and their mineral contents are manifestly precipitated by exposure to the air that we get any traces of yellow; and here, as you and I have both noted, the staining is local and evidently due to the effects of the spring itself. In other words, the marl is the result of selective chemical action and not of such general causes as relation of temperature and release of pressure, even if the degree of saturation of the spring waters is sufficient to allow these causes to become operative in our marl lakes, which is very doubtful, and the doubt even capable of demonstration from existing data, perhaps."

AT ANN ARBOR

At about this time the "inexhaustible supplies of pine" of the Saginaw Valley were exhausted and the Saginaw salt "blocks"—that is, factories—shut down for lack of their fuel of sawmill waste, and the American people began to awake to the fact that they must, like the European nations, grow their own timber. Prof. Volney M. Spalding, of the department of botany of Ann Arbor, recognizing that Davis was, what Newcombe called him, the best field botanist of the State, invited him to organize the forestry courses at Ann Arbor. This he proceeded to do after a half year in the forestry school at Cornell in 1900.

The following letter shows his feelings over the transfer:

"548 Thompson Street,
"Ann Arbor, Michigan.

"What do you think of the forestry business? I probably shall never have a better chance to get into a botanical field that will be more to my liking. The field at Alma is too broad for me to cover and seems likely to get wider as the years go by, and I shall be stretched thinner and thinner, until some day I shall pull apart somewhere, and that will be the end."

Biographers sometimes slur the seamy side of things. This letter of July 11, 1901, from Ann Arbor, referring to his transition from Alma to Ann Arbor, shows some of his troubles there:

"548 Thompson Street,
"Ann Arbor, Michigan, *July* 11, 1901.

"I have decided to take up the forestry work and was elected yesterday by the regents and given a half year's leave of absence in which to fit myself in technical forestry, and shall go to Cornell for the work.

"In regard to the work at Alma, I think I can say that I have done my best there for the 14 years I have been there and have tried to make the president and trustees see that if the work was to be of any value there must be growth on the part of the instructor in charge, and they have persistently refused to give me more than the most perfunctory attention, and have let the work go on piling up on me until it was bad both for me and for the college, as it was impossible for me to do good or satisfactory work under such pressure as was brought to bear on me. Now, the college can put in West, my assistant last term, who is well trained and well qualified in chemistry to take that field, and get another fellow of like experience to do the biology, and I never will be missed, except temporarily, while the new adjustment is being made.

"I do not want you to think I am bitter about Alma, for I have a very strong sentiment about the college, and have put in too many years' hard work there to be bitter, only I do want you to see that the chances for my ever working up to a higher standard in any department were very slim and not altogether or even primarily dependent on my own efforts."

Davis soon perceived that there was room not only for courses in forestry, but for a department of forestry, and so he urged the appointment of Prof. Filibert Roth, who had better acquaintance with the practical side of lumbering.

It would have been better, in my judgment, for him and for the growth of a strong forestry department at Ann Arbor had he kept Davis with him, but Davis' position became smaller and he became only Curator of the Ann Arbor Herbarium in 1905 to 1908. But this may have been fortunate for geologic science, as the State Geological Survey became a more and more important outlet for Davis' scientific work, and in 1904 he was a field assistant on the United States Geological Survey.

The following letters pertain to his life in Ann Arbor in connection with the Survey. First a letter or two regarding the beginning of the Cooperative Topographic Survey:

"303 South Division Street,
"Ann Arbor, Michigan, *February* 2, 1903.

"I think Mr. Hayes fails to realize, quite, the close connection between ecology and geology—at least the historical side of geology. It seems to me that it is here that biology and geology meet, and if ever we are to get at safe approximations as to the length of time taken to develop certain given rock systems, we must study by biological and 'ecological' methods combined with geological studies on the conditions which we find existing in favorable places at the present time. In other words, ecology is one of the meeting grounds of biology and geology, as we ordinarily understand the term, and money spent in ecological work of the right sort might properly come from a geological source, as it would eventually, at any rate, help to solve strictly geological problems."

"303 South Division Street,
"Ann Arbor, Michigan, *March* 20, 1903.

"Having just received the topographic map of the region about Ann Arbor which has been made for the Michigan Geological Survey by the United States Survey, I write to congratulate you on having made such a good start on such an important work. From the standpoint of an educator, I can say that I believe nothing has ever been done in the State which will be of such value in teaching geography, certain phases of geology, and physiography as this; for it will give teachers an absolutely correct and reliable map, not only showing the streams and lakes of the region, but all the relief forms as well; hills, valleys, plains, and old beach lines are all shown in a surprising way and one which should be easily understood by the children. As a worker in the field in various departments of natural history, but especially in forestry, I find it hard to express the feeling of thankfulness which I have that I can have this map to aid me in working out local conditions. It greatly simplifies the mapping of the distribution of different types of forest trees, hence of forests, and will enable me to accomplish much more in a given time than if only the old inaccurate privately published maps were available. Certain kinds of surface configuration are accompanied by certain types of soil, and on this we know there will be found certain kinds of forests; so by simply inspecting this map one may definitely prophesy what kinds of forests may be found in given districts covered by the map. In botany, zoology, and geology these facts obtain also, so that investigators in these lines are equally benefited. Real-estate men here are very much interested in the map and say it means the saving of an immense amount of time to them, for they have the country spread out before them in their office and need not visit it to decide on the character of the land.

"Personally I believe also that for all engineering enterprises the map will be very helpful. I know in investigating sources of water supply about Ann Arbor I have found advance sheets of the map, with its accurate level lines, a great help in my study, since it enabled me to show the feasibility of several sources of supply and the disadvantage of others, without making any survey at all. Aside from the scientific importance of this map, it would seem that it has great business importance as well, as illustrated by the facts stated above, and I trust the work of mapping other portions of the State may be undertaken by your survey.

"I wish to express my sincere thanks for the map and assure you once more of the great help it will be to me."

There has been a long debate as to the character of the Ann Arbor water supply, as to which he writes, on December 12, 1902, as follows:

"The regents are again considering water supply for the campus. This, by the way, is sub rosa at present; but I have been called in as sort of general suggester by the committee in charge and have been going over the possibilities as to the source of such a supply.

"Leverett, Russell, Sherzer, and I had a little love feast yesterday afternoon and tried to get together on the water matter, but Sherzer stuck to his position regarding possibilities of supply, and made a plausible, but not especially convincing, case. Leverett hoped to have an agreement of views published as a result of the conference, but there were so few of the disputed points which could be agreed on that no truce was declared and no treaty signed."

Expert on Peat

The great coal strike had caused a great growth in interest in peat. Michigan peat has also had a great field as fertilizer and stockyard tankage absorbent. Many companies formed ostensibly to exploit peat seemed to be more to exploit the public by stock jobbing, and a State report was called for, which should, on the one hand, give some account of the resources of the State in peat and its origin and possible production, and on the other a review of what had been done by machinery with peat, that the same blunders might not be endlessly repeated. This assigned task Davis completed so successfully that "Davis on Peat" became a classic, and Davis himself the peat expert of the United States. Part of this report on certain of the ecological phases formed his thesis for Ph. D., which was conferred at Ann Arbor in 1905. The practical peat men recognized his courtesy and his fairness of mind even while he criticized, and his American ability in judging machinery and making constructive and helpful suggestions; but his scientific work in discovering the variety of vegetable deposits that at times made peat and the varying ecology and layers of different origin in different bogs did not fail of recognition by such men as David White and E. C. Jeffrey. His long training and study in the dissection of peat deposits led to the recognition of algæ in the oil shales and of signs of vegetal origin in Precambrian limestone, on which subjects he was engaged when death cast his mantle on other shoulders, leaving salients of scientific attack to be occupied and widened by others. As always, the ever broadening area of his knowledge was bounded by an ever larger circle of problems awaiting solution.

His recognition of the different methods of bog filling has modified the older conceptions.

We have referred to the peat-bogs in the letters already cited. Here are others that show his methods of work:

"ANN ARBOR, MICHIGAN, *July* 14, 1903.

"I have been out around Ann Arbor into the bogs and lakes almost continuously since the middle of June, and am beginning to see that the peat question is really an interesting scientific problem—rather a bigger and more complicated one than that involved in the marl. It is not, however, to be solved by studying the old peat-bogs, if I see the situation correctly, for the work is done when the stage which we call a peat-bog is reached; at least, here in this region that is true, and the plants which are found growing in the bogs are simply transient and ever changing population, moving on and off in a pretty well defined order and from easily demonstrable causes. My plan of work so far has been as follows:

"(1) To visit all the bogs which Allen has examined to see what the conditions on these were.

"(2) To visit and study different types of bogs in various types of surface configuration in this vicinity, such as the drainage channel bog, the till plain bog, and the morainal bog.

"(3) To examine carefully the numerous lakes in the district about Ann Arbor to see if there was any difference in their rate of filling, in the plants about them, and if there was any easily discovered relation between any set of plants and the rate of filling.

"(4) To list the plants in all the localities visited to see if in the end the conclusions would be borne out by the plants themselves—that is, to see if these heterogeneously collected lists would arrange themselves into classes.

"I think I could even now give a pretty close approximation to the true situation in regard to peat beds as they are made here, and could show conclusively that the talk about sphagnum peat and other kinds of peat is based on a misunderstanding, but I want more data before coming out with any such statements, of course. It must be understood, too, that my conclusions now forming are based on studies made here at about the southern limit of peat-bogs.

"In regard to the Tuscola report, I am all through with the contour map, thank the Lord!"

"ANN ARBOR, MICHIGAN, *December* 5, 1904.

"In regard to the poison theory, I am not at all sure that there is much of any basis for it, except that in some European bogs the waters have been found to be acid, and the soils also more or less so, from excess of the humic acids; but the amount of such poison, if poison it is, must be exceedingly variable in the soil zone in which the roots of the plants lie, and there must be periods of considerable length, when rains occur so frequently during the rainy growing seasons, that there is practically no excess of acid of any sort present, and, moreover, King and Jeffreys found the peaty soils in Wisconsin were usually alkaline from excess of $MgCO_3$, so much so that crops were decidedly injured by the salt. I have a little new light myself which may develop into something fairly important as one factor, but I am going to investigate it somewhat before I spring it, but it is promising, more so than anything I have struck lately; but I am quite sure that no one factor is the *only* one, so I am simply looking for the controlling one. It is easier for most of us to speculate in the study than to investigate in the field and laboratory, and often after we get results it is difficult to know what to do with them!"

"ANN ARBOR, MICHIGAN, *December* 8, 1904.

"About the prairie business, I will give you the benefit of my cogitations (not my experiments) on the subject immediately. From my observations in the marsh and prairie lands in Tuscola County and in other parts of the State, I have attributed the absence of trees in these places to three causes: (1) The high water for several weeks in the spring, which prevented germination taking place or submerged the seedlings for a fatally long period after germination. (2) The absence of mineral soil in sufficient quantity to permit the growth of trees during the early part of their life history. (3) The generally high soil water level of these places. A fourth and perhaps generally important factor might be taken into account—that is, the dense growth of sedges and grasses in the prairie soil—which first keeps the seeds of trees from reaching the ground and then, later, overshadows those that do reach it and prevents germination or destroys the young plants by shading them too much.

"To support these hypotheses there is the following: When I first went over the prairies in Tuscola County, there were no trees or shrubs except on the 'islands' of sand in the marshes, and the treeline was very definite and sharp inshore, with no fringe of young growth reaching out on to the prairie; but the last time I was over there not only shrubs, but trees, especially poplars and willows, were forming dense thickets all over the area, and for several hundred feet out from the 'treeline' were young trees of the species common in the woods, which were four or five years old, making a thrifty and well marked fringe to the old woods. I attributed this sudden development in this type of vegetation to the building of roads across the prairies and the consequent and subsequent ditching which has covered the whole area with a network of drains, which not only carry off the water rapidly in the spring, but lower the water level in the soil throughout the rest of the year, and this tends to diminish the humus content by drying, kills out the grasses and sedges, and in various ways makes the soil conditions favorable to tree growth, and as the trees are always standing around the edge waiting to get in, there is no trouble about their advancing as soon as they can without getting their feet too wet. On the sand islands the soil was slightly above the general level and sufficiently porous to drain itself readily and quickly after the spring floods subsided. I have never given the Saint Clair flats attention enough to know whether the same state of affairs is to be found there as around Saginaw Bay or not, but expect conditions are about the same."

From the Upper Peninsula of Michigan, working with Russell, he writes:

"CAMP NO. 9, NEAR WAUCEDAH, MICHIGAN, *July* 23, 1905.

"We are certainly getting our share of 'regen,' as our German host put it last night, but manage to keep moving.

"I have found several interesting places since I saw you: one, the bog at Nathan, which I went to the day after I saw you, was a real spruce bog with abundant sphagnum, but not to the margin of the open waters. The other was a small lake near Merrymans Lake (sections 33 and 34, townships 37 and 38 north, range 28 west). This was of rather an unusual type and unexpected in the Upper Peninsula, since the plant making the advance off from shore was *Decodon verticillatus*, swamp loosestrife, supposed to be found only in the C. and S. peats of the Lower Peninsula, but certainly here and doing business. It grows as a perennial, in clumps or stools, but dies back to the water's level or about there each fall. It makes long, slender branches, which grow several feet long and droop at the tips, and when they reach water take root and send up shoots, establishing new plants one or more feet away from the old ones, and since the connection is only maintained a single year the new plant is independent by the fall of the year it starts. The stools eventually become a foot or more across and on them other plants find satisfactory foothold to work out over the water. The substratum in this little lake was undoubtedly formed by some of the few-celled algæ, which made a soft, very light colored peat (?) perfectly distinct from any of the other types of macerated vegetable material occurring in the bogs south.

"Russell says this region we are going into around Iron Mountain has many lakes in it, and I think it would be well for me to stay with him for a while longer, at least until I exhaust the possibilities of this region, for so far the mature swamps show nothing new, although there are some plants wanting which occur below and a few here which are not found there."

"ANN ARBOR, MICHIGAN, *November* 6, 1905.

"I wish you would let me know just what sort of report on my work last summer you want. I have been working on the utilization and technical side of the peat question and am trying to make a well balanced paper of that, and I have also a partial revision of my thesis planned out and some of the work on it done and some of the illustrations done, too.

"One of the interesting things which I have found in working over some of the algal material about which I told you is that there are a large number of conifer pollen grains, and these retain their structure perfectly and are easily recognizable after all structure has disappeared from the rest of the material, which is almost wholly made up of unicellular algæ. Of course, diatoms are present and are not destroyed in the general breaking down. This interesting find naturally suggests that some of the cannel coals which have been described as composed of pollen, or its equivalent, from the carboniferous flora may have been principally algæ, and the pollen grains may have been all that is left of the material, the structure of the algæ entirely disappearing. It was Huxley, wasn't it, who described the pollen coal?"

Transfer to Washington

The position at Ann Arbor grew more difficult. On the death of Professor Russell he had hoped that he might get transferred into the Geological Department. But President Angell wanted a brilliant and well known geologist and found him in W. H. Hobbs.

"Ann Arbor, Michigan, *May* 8, 1906.

"Yours received yesterday. Regarding the various matters therein, I will say that (1) I am taking two of Russell's classes, which come three days per week each, both elementary courses, and do not think they will interfere seriously with my writing, as I have frequently been over the same work with other classes. (2) No plans have even been broached regarding the future of the work. I doubt, however, if any reorganization is attempted at present, as President Angell thinks it not necessary to do all here that is done in other universities; in fact, says that it is gradually coming around to the point where the various institutions can not do more than specialize in one or two directions, leaving others to do other lines of work more thoroughly. I would like to take up permanently the work that Russell has been doing, changing the character of it very little, but making teaching a good deal more prominent and working up some field courses which would be the means of stirring up an interest in the subject. In order to do this, I should have to have free hand, such as only a man above the assistant professor can have. I am going to apply for the place, and any word that you can put in in my behalf will be much appreciated. It has been your encouragement and help that have made it possible for me to make any claim in the matter, and I shall appreciate your further advice, suggestions, and such recommendations as you may be able to give me. Remember, if you please, that I taught geology and physiography at Alma throughout my stay there, and that I twice taught it here in the summer school, and was urged to go on with that work after I made the break into forestry, but did not because Roth didn't want me to. Of course, it is very probable that some one else will get the place, and I am not counting at all on it myself. but I feel that I ought to try for it. My graduate work included geology.

"Regarding the work for the summer, I am counting on doing the Upper Peninsula work in any case. It is not likely that I shall know one way or the other about the place for next year until late summer, and I must keep an eye out for my income just the same, and it is not a bad thing for me to be able to say that I am going into the Upper Peninsula to continue the work that Russell has been doing there, even when it is understood that he would not have continued it anyway because of more congenial work elsewhere. Then the field-work is stimulating and helpful for future thought and discussion."

Working in Upper Michigan with Leverett and Russell, studying the peat and the forests, he could hardly fail to become interested in the surface and glacial geology. His last work for the State Survey, never published by it, was in this field, but some account is given in letters which I started to include, but have omitted for brevity. I shall be glad to show them to any one interested.

Hardly had he finished his work on peat for the Michigan Survey when the call came to take up the same work in the wider field of the United States, in 1907. The family headquarters were removed to Washington, but in the next few years Davis was all over the United States, cooperating with various State surveys in their work on peat.

The trip he made to the Great Dismal Swamp led to the recognition of Lake Drummond as a type of lake which might develop in the formation of a peneplain, and be a sign not of youth, but of old age. After a reconnaissance of the peat of the coastal plain clear way down to Florida, the work in New York closely paralleled that of Michigan; but when in 1907 to 1909 the work of peat investigation began in Connecticut he found fresh-water peat below salt-water peat, and thus his attention was called to that evidence of subsidence or submergence along the Atlantic coast, to which he has added so materially. He clearly saw the real point, not that there has been oscillations of the strand both up and down since the ice age—this no one denies—but there is now going on a submergence of the land around Boston at such an appreciable rate as a foot a century. It was Davis' service that he pointed out the lines of investigation which might indicate not merely submergence sometime, but present and continuous—investigations which have been answered only by assuming that the submergence is relative to the high tide level, and that this has grown greater, while the general average sealevel has not changed. On his work in this direction not many letters are needed, as this Society has already published notes about it.

In his studies of seacoast subsidence, 1910 to 1916, he has acted as protagonist of the botanists and believers in subsidence against D. W. Johnson, who is equally imbued with the scientific spirit and with whom his personal relations were most friendly. To be sure, Davis, like the rest of us, sought for facts on that side of the case which he favored.

Those of us who were at the New England intercollegiate excursion of 1911 will remember the debate between Davis and Johnson on the Medford marshes, where the salt-water peat swathes great pine stumps growing in place, lasting until the moon rose and we "felt the damp of the river fog that rises when the sun goes down." But not so many know that, inspired by that discussion, during the excursion Davis thought of the railroad cinders in the peat as a measure of the upgrowth of the variety of peat formed almost wholly of plants that only grow at extreme high tide level and slipped off with his sampler and brought back before the close of the excursion and discussion samples that showed the upgrowth of the peat and of the high water level—4 inches in the sixty years since coal-burning railroads ran across the Lynn marshes.

He was, however, scrupulously careful in observing and stating his facts as distinct from his inferences and glad to be challenged, and there is no doubt that this discussion has aided wonderfully in making clear the difference between proof that coastal subsidence is now going on and proof that it has gone on in the past.

"WASHINGTON, D. C., *June* 21, 1909.

"I find that mental keys, like others, are likely to get lost just when they are wanted, so I usually carry a notebook and put such convenient matters, as addresses, etcetera, down in it.

"Our friend, David White, has just opened up the box of coal fossils I sent him from Michigan, from the old Pere Marquette number 3 shaft, and on casual inspection says it is the best lot of stuff he has seen from the Michigan coal field."

"WASHINGTON, D. C., *March* 18, 1910.

"All winter I have been putting in my evenings reading proof of that everlasting Tuscola report, and I have come to the conclusion that you were quite right about Cooper—he was a good man to read proof and attend to editing, for the proof he used to send me was much less raw and crude than that that I have had, now that he is gone. That is not what I am writing about, however. At the last moment Wright informs me that I have lost my appendix—not my vermiform, but next higher in the scale, my molluscoidean appendix. It seems that you added to the table of contents, 'Appendix—Mollusca of Tuscola County, by Bryant Walker,' and the manuscript was submitted printed, galley proofed, and page proofed down to the last lot of pages, and it has just been discovered that there is no appendix, mollusca, etcetera, and I am writing you to drop a note to Wright and tell him what you know about my helicoid appendix and why it has been removed, if you have any recollection about it. I also have written Walker to tell Wright what he knows about the same appendix, and thus, since I have written him all I know about it, he will get information enough to enable him to find the manuscript, to know whether he is to wait for a new one or to cut out the appendix from the bowels of Chapter VIII, to which it is now attached."

The following illustrates his thoughtfulness for his friends and for scientific material:

"WASHINGTON, D. C., *April* 7, 1910.

"I sent you today a bunch of pictures that I rescued from the waste basket some days ago. Many of them are without labels, but they may come in handy to pass around to illustrate certain points or to have slides made from [they were]. If not they can still go into the waste basket or be turned over to the children to play with. Some have labels."

His yearning for more facts and the reconciliation that comes in knowing all the facts is well expressed in this letter, as well as the nursing of his wife, which was an important part of his life.

"WASHINGTON, *October* 24, 1910.

"You will probably be surprised to get a letter from me at home after what I wrote you from Kittery. Scarcely had I written my last letter, however, when Mrs. Davis took a turn upward physically and the doctor said she could be taken home, especially as she was very homesick.

"To tell the truth, I had been acting as nurse so continuously that I was pretty well played out at that time.

"Regarding the matter of the observations on the vegetation affected by the breaking of the barrier beach down on the Cape, once more, while I can see that occasionally the cause which produced the conditions we observed there may be operative, I can not see how they are likely to be of general occurrence. Moreover, I do not see any way in which we can account for submergence of tree stumps in places to a depth of 9, 10, or even 12 feet by such a cause, and certainly I am unable to account for the homogeneous structure of the salt-marsh turf, made up of *Spartina patens* remains to the depth of several feet, by this method.

"I am greatly interested in Johnson's Nantasket problem, and when I get a chance I hope to go down and go over the ground there, not to question his conclusions, but to get the lay of things better in mind. There must be a way in which all of the facts we have before us can be reconciled, and the explanation must be general in its application. I suspect that it lies in a slower rate of subsidence than we have been considering, but have not been able to get any evidence along that line as yet; and even then it is hard to reconcile the subsidence recorded at many points on the coast from Eastport to New York with the beach ridges at Nantasket, as Johnson interprets them, the oldest ridge practically at the present sealevel, and yet during its existence all of the erosion which has to be assumed, according to Johnson, has taken place. I can not see, however, that your suggestion that the Nahant case I cited is insignificant because the whole section may have been cut back would hold unless we assume that there has been extensive cutting at Nantasket as well, and that Johnson is quite strenuous in denying.

"No, when we get all the facts we shall be in accord. I am willing to let the matter rest until I can get more records and digest them. In the meantime hammer away at me with all the objections you may think of."

I sent him a sample of peat occurring in an interesting channel exposed in a cellar on Holland street, near Davis Square, cut in the fine sand and overlaid by a few feet of gravel, indicating apparently that the Cambridge gravel plain has a double origin. He writes a letter of interest to those who are making out two ice deposits hereabouts:

"DEPARTMENT OF THE INTERIOR,
"WASHINGTON, D. C., *December* 1, 1910.

"Yours with the interesting peat sample duly received this morning, and, if possible, I would like some more of the same, and am sending you a bottle in mailing tube and inclose frank herewith (if I don't forget it) for the return of the specimen.

"The material has abundant fragments of wood in it, and it is possible that by looking carefully you may get some that are of good size, and there *might* be some seeds in such matter also.

"One notable thing about the vegetable matter is the high degree of carbonization which it shows. It is not charred by fire, as shown in thin sections, but is carbonized very much more than similar matter that I have received from the old beaches in Illinois, where the vegetable matter is still so fresh that it preserves all of its characteristics, including the power to absorb water. I collected some woody matter along the Evanston Canal during the summer, which was perhaps 10 feet below the surface, in one of the Lake Chicago bars, that was almost fresh—much more so than the wood often found in peat. Why this deposit of yours so near the surface should show so much carbonization I do not see, unless it is very much older than the Wisconsin drift. You may remember some wood that Cooper found in one of the shafts in Bay County that had a similar old look to this stuff from your cellar hole, except it was not so thoroughly carbonized.

"I am much interested in Johnson's work on the marshes.

"As a matter of fact, the very North River marsh which he cites to explain the occurrence of stumps in all marshes in ten years has made a record that gives it a different structure from any other marsh which I have seen, and shows that this is a special case and can not be used to account for the formation of any other marsh I have examined.

"The fundamental principle on which I have been working is that identical species grew in the past under conditions that are the same as those under which they are now growing; hence if we find, as we do, that the salt marshes contain several feet of material made up of plants which now grow only on the surface of the marshes where the average tide just reaches them, I feel certain that the growth of the deposit began when the high tide just reached the lowest stratum of these remains, and that each successive inch of the deposit was for the time when it was formed the surface of the marsh, and does not mean that the tide covered the surface to an average depth of 2 to 3 feet for long periods of time while the marsh was being built up. If such were the history, there is not the slightest doubt that it would be recorded in the marshes themselves by differences in structure. Moreover, if, as Johnson says positively, there has been no subsidence for at least 3,000 years, there would not be an acre of salt marsh in New England, for there is no chance for doubt that at the present rate of silting these would long ago have been built up to a level where the brackish-water plants would have come in: and as these include some very rapid peat builders. such as the cat-tails and *Scirpus americanus*, even if a minimum rate of building is assumed, the salt marshes would have been eliminated.

"However, of this 'more anon'; but you see there are some things that can still be said on the side I am espousing."

The following extract shows what he was doing in 1911;

"JOURNAL OF THE AMERICAN PEAT SOCIETY,
"WASHINGTON, D. C., *January* 4, 1911.

"On the whole, I was glad I went to Pittsburgh, although I was sorry you were not there, and that Johnson was also absent, as I would have been glad to discuss the North River marsh and its significance with him in public. The material from Neponset marshes which he sent me for examination falls beautifully into line with other evidence I have and contains nothing to show that I am wrong in my own observations and deductions, or to show that marsh building takes place in any but a very steady way, except under such unusual conditions as we found at North River."

In 1912 he visited Germany. The following letters refers to this and details the plans he executed in 1913:

"WASHINGTON, *April* 21, 1913.

"I wish I had time to write you about my trip to Germany, but it is too long a story for a letter, and I will postpone it in the hope that I shall see you in the not far-distant future, when I can tell you about it. It was entirely unexpected and very profitable, both professionally, in enlightening me in many ways on peat and its uses, and financially, as I got a good fee for my report and the time spent on the trip, which was taken as annual leave from my regular job.

"As to summer plans, they are still in the air; but possibly I shall go to New England about June 1 and work in Maine around Portland for the month, and then go to Massachusetts for a month or six weeks and work up one or more quadrangles adjoining those I have been at work on. This work will be done for the United States Geological Survey. Then in August sometime I plan to go to Duluth and begin work in northeast Minnesota, which will be interesting, as it will supplement my Upper Peninsula, Michigan, work and, I hope, give me a chance to work on some more of those so-called 'algal' deposits, which are not algal at all; but so far I have not found any one who can tell me what the active organism really is."

"WASHINGTON, *November* 20, 1913.

"I spent about six weeks examining the big muskegs in northeast Minnesota. These are much more extensive than anything I have seen elsewhere, and are very similar in structure and origin to the high moors of Europe, although in a more primitive condition. Leverett was at Duluth much of the time I was there and we made a good many trips together. On one trip we walked at least 75 miles in three days, 'living on the country,' as Leverett always does."

"DEPARTMENT OF THE INTERIOR, WASHINGTON, *April* 11, 1914.

"MY DEAR LANE: Last summer, while working along the coast north of Boston, I made a little study of the north end of Revere Beach, that part especially which is called 'Point of Pines,' which name, by the way, brings up many interesting reminiscences of our Michigan days. I found that the Point of Pines was really a series of beach ridges, and although the higher parts of these had been removed in grading, it was still possible to determine the relative heights of most of them, and if I could see correctly[4] the oldest of these ridges were lower than the newest were. The parts of the ridges which have been least disturbed are those which lie on the west side of the Lynnway and the Revere Beach and Lynn Railroad. Here, in the salt marsh, there is a series of spits which run back from the beaches into the marsh, and the oldest ones again are certainly lower than the most recent, as is shown both by the vegetation and by actual observation of the tide-marks."

In 1914 Davis spent a good deal of time in Minnesota and Utah with David White, whom as an equally good geologist and botanist and as companionable a man he had found a kindred soul. White introduced him to the leaf peat and brown oil shales of the West.

In 1915 Davis was back in Maine once more, amid the scenes of his youth, still at work on peat and thinking of subsidence.

When I came to the Washington meeting, Christmas, 1915, I found him looking extra pale and worn, as he had been nursing his wife nights and doing his work by day—burning the candle at both ends. He tried to attend the meetings with his usual faithfulness, but found it a good deal of a task. And I remember how glad we were to go off and see Gerty, the trained Dinosaur, at the moving pictures one afternoon.

The last postal I have from him was dated February 9, 1916, and he writes:

> "Yours just received. The last few weeks I have been working on a series of natural organic substances, apparently derived from peat or lignite, and hope before long to get out a paper on them, as they may have some scientific interest and possibly also some economic value. Am sorry I cannot go to New York at this time. The Bureau will undoubtedly be represented there by several of the engineers."

The letter to C. K. Dodge, above cited, was later. Only a short time after this came the news that he was dangerously ill. Acute Brights disease soon did its fatal work and he passed from this life April 9, 1916. His body was carried back to Portsmouth.

While impressing one as slow in speech, quiet, kindly and genial rather than jovial, he had a keen appreciation of his wife's wit, and his occasional sallies were all the more brilliant and like an occasional flash of lightning as contrasted with the coruscations of his wife. For instance, the family were gathered at the windows of the house in Ann Arbor watching the passers-by scurrying from before the drops of a sudden thunder-storm. Down the street came a large and majestic negress as slowly as though the rain had not begun. "Look at that colored woman.

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[4] The work was done. His eye did not deceive him.

Why doesn't she run?" was his wife's ejaculation. "Fast black and won't run" was Davis' instant application of the familiar advertising phrase.

As member of the Michigan and Washington Academy of Sciences, the American Association for the Advancement of Science, the American Peat Society, the Washington Geological, Botanical and Biological Society, this and the Washington Geological Society, and corresponding member of the New England Botanical Club, he was always helpful and ready to do his share. He also was a member of the Cosmos Club.

From the botanist's viewpoint Prof. E. C. Jeffrey writes:

> "Doctor Davis' work on peat is the most valuable that has been done. He did not content himself with the examination of deposits from the surface only, as has been the practice of too many American investigators. In his case necessity was truly the mother of invention; for, unlike European students, he did not find peat deposits opened to investigation by industrial exploitation. As a result of this situation he was led to the invention of a probing instrument of precision, which makes possible the investigation of the otherwise inaccessible accumulations of vegetable matter in the bottoms of lakes. He arrived at the very interesting and highly significant conclusion that the great mass of accumulated vegetable matter within the boundaries of the United States had been laid down under the surface of open water. This conclusion is not the less valid because Doctor Davis shared the orthodox view that coal deposits were of terrestrial origin. His last efforts were in the direction of showing the existence of algæ with structure recognizably preserved in lignitic coals of the Western States. Doctor Davis' personality, although not at first meeting impressive, became with longer acquaintance appreciated as of rare worth. His personal kindliness tempered his stern and Puritanic scientific sense of honor. His untimely death is a great loss to American botany and American geology."

While Davis' turn of mind was eminently scientific and his first words were of algæ in black shales or Precambrian limestones, or some new light on the subsidence question, and while he refused $10,000 a year to go into private employ, he never forgot those men who were trying to make peat of the greatest use to mankind, and as a charter member of the American Peat Society and editor of its journal from its foundation, in 1908, until his death, he worked untiringly for their interests—a work recognized by them in formal engraved resolutions reproduced in his memorial in the Journal of the American Peat Society, volume IX, number 3.

I can not close this memorial of his departure from the particular material form through which we knew him without recording that peculiarly vivid belief in, and sense of, a life beyond this life, which the intimacy of the camp-fire and long field trips together led him to express in spite of the fact that he was not a talkative man on these or other matters. Some would have considered his views tinged with spiritualism, but they were balanced by his sound religious faith.

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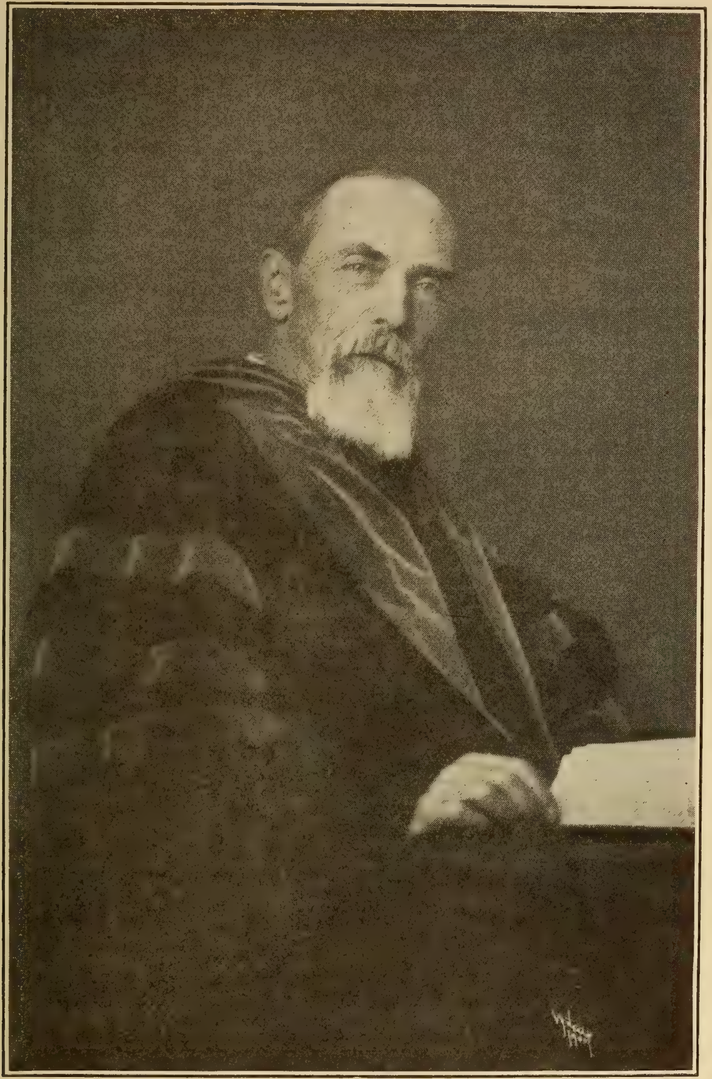
MEMORIAL OF EUGENE WOLDEMAR HILGARD

BY EUGENE A. SMITH

Eugene Woldemar, a son of Theodore Erasmus and Margarethe Hilgard, was born January 5, 1833, at Zweibrucken, in Rhenish Bavaria. His father was a lawyer, holding the position of Chief Justice of the Court of Appeals of the Province. In 1836, for political reasons, Judge Hilgard came to America with his family and settled on a farm at Belleville, Illinois. Here Eugene passed his early years, receiving instruction mainly from his father and from his home library and devoting his spare time to botanizing and insect collecting. At the age of 16, because of failure of his eyes, he was sent to Washington, D. C., to visit his brother Julius, then assistant on the United States Coast Survey. Attending lectures on chemistry in the Homeopathic Medical College and the Franklin Institute, he soon became lecture assistant in the former. In 1849 he returned to Germany and entered the University of Heidelberg,



Yours truly
Eug W. Hilgard

but on account of political trouble there existing at the time he changed to the University of Zurich, and then to the Royal Mining School at Freiberg, in Saxony, returning later to Heidelberg, where in 1853 he received the degree Ph. D. *summa cum laude* at the age of 20.

In 1853, on account of continued ill health, he visited the coast of Spain, where he spent two years in geological investigations. Here he met Miss J. Alexandrina Bello, daughter of Colonel Bello, of the Spanish army at Madrid. She became his wife in 1860.

In 1855 he returned to Washington and fitted up a small chemical laboratory in the Smithsonian Institution, but later in that year he accepted the position of assistant on the Geological Survey of Mississippi, then under the direction of Lewis Harper. In 1857 the Mississippi Survey was suspended by the legislature, and Hilgard returned to Washington as chemist in the laboratory of the Smithsonian Institution and lecturer on chemistry in the National Medical College.

On the revival of the Mississippi Survey in 1858 he was appointed State Geologist, and the next two years were devoted by him to detailed investigations of the geology, botany, agriculture, and other economic features of the State and the preparation of his report on these investigations. This report was in great part written while he was making the chemical analyses of soils and marls and other useful materials. The work extended often far into the night, when, in the intervals between his chemical manipulations, he wrote up his manuscript, for he had to finish this report before going back to Spain, in August, 1860, to claim his bride. As he states it:

> "But several forms [of the report] were not yet in print when in August imperative matters called me to Europe, and Prof. W. D. Moore undertook to see the remainder of the work through the press."

Returning to the University of Mississippi with his wife, he found the State in the throes of war; the exercises of the university were suspended, and as State Geologist he was placed by the Governor in charge of the library and other possessions of the university. Later he was appointed an agent of the Confederate Nitre Bureau, and during the siege of Vicksburg was ordered to erect calcium lights on the bluffs for the illumination of Federal gunboats in their attempt to pass the city. The fleet, however, got by before he could complete his arrangements for the lights. It was at Vicksburg that he contracted bodily ills which seriously affected his health for the rest of his life.

In 1866, twelve months after the close of the Civil War, the Geological Survey of Mississippi was revived, *ipso facto* on the basis of the act of

1860, and Hilgard's report, printed in 1860, but held in the binder's hands through the entire period of the war, became available for distribution only in 1866. In October of this year Hilgard resigned his position of State Geologist and accepted that of Professor of Chemistry in the University of Mississippi. His successor as State Geologist was Dr. George Little, his former assistant.

In October, 1870, Doctor Little accepted the Professorship of Geology and Natural History in the university, and Doctor Hilgard, to prevent the Survey from being either abolished or falling into wrong hands, again assumed its direction, which he continued to hold, but without extra compensation, until 1873, when he was called to the University of Michigan as Professor of Geology and Natural History. After two years' service in Michigan, he went, early in 1875, to the University of California as Professor of Agriculture and Director of the Agricultural Experiment Station, which he founded there in 1875. The rest of his life was spent at this institution.

From 1879 to 1883 he was special agent in charge of the report on cotton culture for the Tenth Census. During part of this time also, from 1881 to 1883, he was in charge of the Agricultural Division of the Northern Transcontinental Survey.

After going to California, Doctor Hilgard came east only three times: in 1889 on the death of his only son, a student in Columbia University. In 1891 he attended the meeting of the International Geological Congress in Washington, and after the close of the meeting he took part in an excursion down the Mississippi River from Memphis to New Orleans, reviewing the exposures along the river and in its immediate vicinity. With him on this occasion were Dr. W J McGee, Mrs. McGee, Robert T. Hill, Joseph A. Holmes, Dr. James M. Safford, Prof. Lester Ward, and Eugene A. Smith. In 1893 he visited Europe, where he was the recipient of many honors from scientific men, universities, and experiment stations.

During the active period of his life Doctor Hilgard suffered two great bereavements—the loss of an only son in 1889 and in 1893 the loss of his wife. In 1905 he retired from active service in the university and became Emeritus Professor of Agriculture. He died January 8, 1916, at the age of 83.

For his graduation thesis in 1854 Hilgard selected the investigation of the luminous flame, in which he described the processes which go forward in the four parts of the flame. His first contribution to the American Association for the Advancement of Science was in 1857, "On the quantitative assay of chromium by blow-pipe processes." He was an expert in blow-pipe manipulation, and in his report in 1869 for some Mississippi clients, on a Mexican silver mine, all his estimates of values were based on quantitative blow-pipe assays.

His first scientific work in the Mississippi embayment region began in 1855, when he accepted the position on the Geological Survey of Mississippi, "amid the sincere condolence of his scientific friends on his assignment to so uninteresting a field, where the Paleozoic formations (then occupying almost exclusively the minds of American geologists) were unrepresented." On his way south he paid a visit of several days to Dr. David Dale Owen and his assistants, E. T. Cox and S. S. Lyon. This visit was most important and fruitful in giving direction to his subsequent studies and methods.

The notes of the first two years of Hilgard's Mississippi work were incorporated in the report of L. Harper, State Geologist, published in 1857, but with such misrepresentations and distortions that Hilgard made public denial of all responsibility therefor. The report of 1860, on the geology and agriculture of Mississippi, is thus the first authentic statement of the results of his personal field, office, and laboratory work during four years, 1855 to 1859.

After a year's experience as assistant on the Geological Survey of Mississippi, he writes:[1]

> "It having become clearly apparent to me by this time (1856) that the Survey would never maintain itself in public esteem on the basis of mineral discoveries, and that it must seek its main support in what services it might render to agriculture, I made a point of paying close attention to and recording the surface features, vegetation, soils, the quality and supply of water, and especially the marls, which I found to occur in large supply and great variety. I also made a collection of plants, which, although omitted from the subjects mentioned in the act creating the Survey, I perceived was essential toward the characterization of soils. In the prosecution of these studies the close connection between the surface vegetation and the underlying formations became so striking that I soon largely availed myself of the former in tracing out the limits of adjacent formations, in searching for outcrops, etcetera."

In our studies of the coastal plain of Alabama the present writer and his assistant, Daniel W. Langdon, have time and again found that the method of geologizing above mentioned, by the native vegetation, is by no means to be neglected or held in slight esteem.

Hilgard continues:

> "In this report (1860) I undertook to separate, as far as possible, the purely scientific part from that bearing directly on practical points, in order to render the latter as accessible to unscientific readers as the nature of the case per-

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[1] Publications of the Mississippi Historical Society, vol. iii, pp. 207-234.

mitted, while at the same time giving scientific discussion full swing in its proper place. . . . The volume is thus divided nearly evenly between a 'geological' and an 'agricultural' portion; the former giving, under the special heading of 'useful materials,' the technically important features of each formation, after its geological characters have been discussed."

This report is one of the classics in its line, as, barring details since worked out and outlines since filled in, it presents the geology of Mississippi practically as it is known at the present day. With Tuomey's reports of Alabama and Safford's of Tennessee, Hilgard's stands easily in the highest rank of the State reports of that day and time, or, for that matter, of any time.

The data for his report on the exceptional character of the Mississippi River delta and for his geological reconnaissance of Louisiana were obtained by him on a trip down the Mississippi River to the passes, made under the auspices of the Smithsonian Institution in 1867, and on another trip in 1869 across the State of Louisiana under the auspices of the New Orleans Academy of Sciences and the Bureau of Immigration of the State of Louisiana. The combined results of these trips and of his previous Mississippi embayment studies have been summarized by him as follows:

"1. The outlining of the Mississippi embayment in Louisiana and Mississippi.

"2. The outline geological study and mapping of these States.

"3. The recognition of the Cretaceous ridge or backbone of Louisiana, from Lake Bistineau to the chain of Salt Islands, and the determination (inferential) of the Cretaceous age of the rock-salt and sulphur deposits of Calcasieu Parish.

"4. Study of the exceptional features of the Lower Mississippi delta and of the mud lumps and their origin, and the definite correlation of the Port Hudson formation."

In his Mississippi geological work, referred to under section 2 above, he was the first to give a clear and definite account of the origin and distribution of the surface formation which he called Orange Sand, but which later, by agreement, received the name Lafayette. While some question has arisen during the last few years as to the appropriateness of the name Lafayette, I think time will confirm Hilgard's conclusions as to the existence of a surface formation over much of the area of the Gulf Coastal Plain, by whatever name it be called, and as to the general mode of its accumulation.

So, also, he was the first to give a definite account of the great series of river and estuarine deposits, the Grand Gulf, representing, as he claimed, all geological time between the Vicksburg and the Lafayette, although no recognizable fossils had been observed by him.

The recent finding in various parts of this territory of beds containing leaf impressions, and their identification as Lower Oligocene, Upper Oligocene, Miocene, and Pliocene respectively, appear to demonstrate the correctness of Hilgard's original conclusion, and the name Grand Gulf will probably stand, or *should stand,* not perhaps as a formation name, but as the collective name of a very definite and apparently unique type of Coastal Plain sediments—or shall I say Mississippi River sediments?

Concerning the agricultural half of his 1860 report, Doctor Hilgard writes:[2]

> "In the special or descriptive portion of the Agricultural Report the State is divided into 'regions' characterized by more or less uniformity of soil and surface features; and each is considered in detail with respect to all natural features bearing on agricultural pursuits, special attention being given to the nature of the soils, as shown by their vegetation and analysis. In the latter respect I departed pointedly from the then prevailing opinions, by which soil analysis was held to be practically useless. My explorations of the State have shown me such intimate connection between the natural vegetation and the varying chemical nature of the underlying strata that have contributed to soil formation as to greatly encourage the belief that definite results could be eliminated from the discussion of a considerable number of analyses of soils carefully observed and classified with respect both to their origin and their natural vegetation and a comparison of these data with the results of cultivation, and that thus it would become possible after all to do what Liebig originally expected could be done, namely, to predict measurably the behavior of soils in cultivation from their chemical composition.
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> "To what extent this expectation has been fulfilled is hardly apparent from the very limited number of analyses which my unaided work was able to furnish for the report of 1860. But the lights then obtained encouraged me to persevere in the same line of investigation, in the face of much adverse criticism, when wider opportunities presented themselves afterward. By the aid of these I think I may fairly claim that the right of soil analysis to be considered as an essential and often decisive factor in the *a priori* estimation of the cultural value of virgin soils has been well established alongside of the limitations imposed by physical and climatic conditions and by previous intervention of culture."

His contributions to the scientific journals until 1875, when he went to California, were mainly in elaboration of his geological work in Louisiana and Mississippi, outlined above, as may be seen in the appended bibliography. During this period there are also many articles from him on agricultural subjects, contributed mostly to the newspapers and to the popular agricultural papers.

In California, while his main work was in connection with his department, in preparing the annual reports of the experiment station and department, and in contributing to the State papers articles on agricultural subjects, he wrote on geological topics also, especially between 1880 and 1883, while in charge of the cotton culture reports of the Tenth Census. He kept up, however, with the geological work done by others in the Gulf Coastal Plain until the day of his death, and we find critical papers from him in Science, American Journal of Science, and other journals, on matters connected with the geology of the Gulf Coastal Plain. His correspondence with the present writer contains many valuable comments on geological topics which have never been in print.

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[2] Publications of the Mississippi Historical Society, vol. iii, p. 224.

On the basis mainly of his Mississippi work, Doctor Hilgard was selected by Gen. Francis A. Walker, Superintendent of the Tenth Census, to supervise the preparation of the reports on cotton culture for that census. He took hold of this new work with his characteristic energy and thoroughness, and from 1879 to 1883 practically all of his time which could be spared from university duties was devoted to it. He himself prepared the general discussions and the special reports on Mississippi, Louisiana, and California. The mass of correspondence which fell on Doctor Hilgard in fitting and adjusting the several State reports and combining them into a harmonious and consistent whole is something difficult to appreciate. His letters in connection with the Alabama and Florida reports alone were of weekly, often daily, occurrence, and are brimful of interesting and entertaining side remarks and quotations.

A full appreciation of Hilgard's gifts as a letter writer can be had only by reading the letters themselves, but I give here, by way of illustration, a few characteristic extracts from our correspondence during this time. Once, when we were laboring on the problems of properly distinguishing between certain agricultural divisions, he wrote:

> "Tell the truth and shame the devil in all cases, and as Torrey once said to Doctor Engelmann, when the latter remarked that few persons could distinguish two certain species of oak from each other, 'When nobody can distinguish them, why distinguish them?' "

And at another time:

> "You worry yourself too much about the manner of doing it, as if you could tell just how by taking forethought: 'Parlez vous comme vous der Schnabel gewachsen ist,' as the German remarked to his Alsatian acquaintance, and write it down, and if it does not suit you, cut it and paste it and turn it inside out."

This advice has often served me a good turn. When speaking about certain county descriptions in the cotton reports, he said:

> "Like some other good things, these descriptions are 'very virtuous, but not at all amusing!' "

"I am now engaged in the tough job of writing up what I have never seen myself to any extent, . . . and as I tell Loughridge, 'It helps you along wonderfully fast when you don't know much about the subject you are describing.' "

"You can not be rigorously consistent in this as in many other things without an occasional *reductio ad absurdum.* And as variety is the spice of life, especially in Mormondom, I don't pretend to stick to the principle as above laid down at the expense of having the heavens fall."

"In this case I must hold with Mr. Gradgrind that 'facts is what we need, sir; hard, solid facts.'

"Since receipt of your letter, I have 'paused for a reply' because of the getting off of my Louisiana MS., 'the first bantling of a brood of twelve,' as I informed the superintendent (General Walker)."

Speaking of our cotton culture maps:

"I don't believe in lines slanting right, left, vertical, and horizontal; they bother me. Give the farmer color and plenty of it, and make the map look pretty, like a pile of calico in the country store."

When overworked and on the point of breaking down, he took a trip into the mountains, remarking, "Ein kluger Feldherr schönt sich." The wisdom of this was shown when he came home after a month's absence with renewed vigor.

"I have just returned from the Upper San Joaquin Valley, where I nearly froze—it being a semitropical climate. But I captured lots of soils and alkali."

In these cotton culture reports Doctor Hilgard followed the precedent set in his 1860 report, modified and amplified, however, by his experience in California with arid soils. The interests of farmers and intending immigrants are kept constantly in view, so that the reports are most reliable handbooks of the States of which they treat, and deserve to be far more widely known than they are.

In a letter of 1913 his final comment on this great work is as follows:

"The Census cotton report, for all the hard work it cost, has found little appreciation because of the medium of publication—quarto at that. Don't let us do it again."

Commenting on this report, Prof. E. J. Wickson says in his address at the memorial services in honor of Doctor Hilgard at the University of California, January 30, 1916:

"But this monumental cotton work, based on the soil work, which was one of its foundation walls, was nation wide in its influences. It was accepted throughout the country as a demonstration that Hilgard could do the work which his California reports and other publications were urging on the public mind. It was a force in engrafting original research on the instructional work, established through the educational land-grant law of Morrill, by the enactment of the Hatch law for experiment stations in all States; and when those institutions were being developed in the latter 80's, Hilgard and the research establishment which he had created in California were the accepted prototypes of men, means, and methods.

"Nor was he simply a national exemplar in his line. When he went abroad for a short time in 1892, after seventeen years of tireless and most productive work in California, he was received with unusual tokens of honor and esteem, and by many learned and scientific bodies was prevailed on to describe his ways of work and the notable differences, which he was first to formulate, of conditions in arid and humid climates in their scientific and economic aspects."

Dr. R. H. Loughridge, from 1871 on the pupil, assistant, colleague, and intimate friend of Doctor Hilgard, was more intimately associated with his work in California than any one else, and no better summary of this work can be given than by quoting the following passages from Loughridge's contribution to the Hilgard memorial exercises held at the University of California in 1916.

Immediately after he went to Berkeley, in 1875, Doctor Hilgard established on the university grounds the first agricultural experiment station in the United States, and

"Prior to 1860 he had established several outlying substations for the study of soil and culture problems peculiar to the several agricultural divisions of the State, which are marked largely by differences in climatic conditions."

"The most important of these was the one at Tulare, in the San Joaquin Valley, established for the purpose of studying alkali problems, in which he took special interest and pride."

"Among his California activities there stand out prominently his studies on humid and arid soils, in which he was the first to point out their differences in depth and in physical and chemical characteristics; he was the first to explain endurance of drouth by culture crops in arid soils and why sandy soils are among the most productive in the arid region and the least so in the humid. He was interested not only in the soils of the United States, but in those of foreign countries and was constantly on the alert for new data."

"His successful researches into the cause and occurrence of alkali salts, their effect on vegetation, and especially the methods to be used in their neutralization and the reclamation of the land in which they occur, are well known. He was the first to enter this field, and the results of his experiments have been extensively quoted and his bulletins published in other countries where alkali lands exist."

"While Professor Hilgard was not the first to make a soil survey or a chemical analysis of the soil, he was the first to interpret the results of analyses in their relation to plant life and productiveness. He was also the first to maintain that the physical properties of a soil are equal in importance to the chemical in determining the cultural value."

To this may be appropriately added the following extract from the address of Prof. E. J. Wickson on the same occasion:

> "The proper relation of agricultural practice to agricultural science, as factors in educational effort; the educational distinction between labor performed for enlightenment and labor prescribed to beget a liking for labor; the place of both the art and science of agriculture in a university of higher learning, when both are handled ably for instructional purposes—these were among his fundamental contentions, upholding them through many controversies, and his victory is seen in their entry into the regular curricula of all of the newer institutions of learning and their pursuit by older institutions established on other standards of learning before the existence of them as educational factors was dreamed of as worthy and capable.
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> "Even the vocational point of view, now so universally prevalent, was clearly occupied in his first report, that of 1877, and the first accession to his staff was an instructor in practical agriculture, in 1878. Thus, at the first opportunity, he justified his conception of the relation of facts and principles, when the natural temptation was to exalt his own personal line of research by proper laboratory provision and equipment."

Doctor Hilgard was of medium height, rather slender, and until his later years remarkably youthful in appearance. Meeting him in 1891, after an interval of 20 years, I could see no signs of advancing age, no gray hairs. He was alert and quick in all his movements. To those who knew him he was one of the most lovable of men.

His extraordinary fund of general as well as of special information, made always available by a never failing memory, along with his cheerfulness and vivacity, notwithstanding the handicap of a rather frail constitution, made him a delightful companion, and his letters, even on technical or scientific matters, were always enlivened by humorous and witty quotations and remarks, so that they are truly "good reading."

He was master of the English language, as may be seen in his numerous writings, and in his spoken word there was nothing of the foreign accent, barring a slight lisp which might have been taken for it. In German, of course, and in French and Spanish he was equally at home and fluent. He read easily also Greek, Latin, Sanscrit, Italian, and Portuguese.

Among the causes contributing to Hilgard's success were, first of all, his mastery of the subjects in which he became interested and his untiring industry, as shown in the long list of his contributions to science. His suave and pleasing address made friends for him everywhere; but with all his geniality and gentleness of manner he could fight most strenuously for his cause when occasion demanded it.

When he became State Geologist of Mississippi, in 1858, he found strong opposition to the Survey among the legislators as well as among the farmers. His first care was to overcome this opposition, which he did in a most characteristic way. He wrote a short report to the Governor on the condition of the Survey, and placed on exhibition at the State fair a collection of soils and marls, which he used in explaining to legislators and farmers the objects of the Survey and its importance to them and to the State. From his previous investigations he was enabled to advise regarding soil peculiarities and needs, and thus won the confidence and support of the masses.

Later, in California he exercised the same tact, ability, and skill in presenting his case, so that he won over to his side successively the farming population, the faculty of the university, the regents of the university, and the legislature of the State. He lived to see his ideas with reference to the dignity and pedagogical value of agricultural science recognized throughout the country.

During the years 1869 to 1871 the present writer was an inmate of Hilgard's house, and was thus thrown into close relations with him and his family, in 1869 consisting of himself and his wife and one son—Eugene, Jr.—then about four years old. Before 1871, however, there came another member—a girl.

This, with the two years following, was a period of great scientific activity with the Doctor, and many of his papers on the geology of Mississippi were written then in his study adjoining the sitting-room, where Mrs. Hilgard, the *Senora,* as he always called her, was accustomed in the evenings to play on the piano, as she was a most accomplished musician. The Doctor, though busy with his writing, yet kept up with the music, as was frequently shown by his applause and request for encores of anything that particularly pleased him. The illustrations to these papers, which were to be read before the American Association for the Advancement of Science, were drawn on large scale on cambric, under his direction, by the present writer, to be displayed before his audiences.

He was an enthusiastic cultivator of flowers as well as vegetables, following in this the Chinese system of fertilizing, which was most efficacious. He had, consequently, the most luxuriant gardens in Oxford, and they were frequently visited by his Oxford friends. The boy, Eugene, then hardly more than a baby, knew the botanical, though not the common, names of most of the flowers. On one occasion, when some visitors were admiring the flowers, one of them spoke of the partridge berry, then in flower. "That's not partridge berry," said the child, "that's *Mitchella repens.*"

On March 1, 1915, he writes:

"The incident [a fall from a step-ladder, which caused the fracture of a bone] came so near terminating my earthly career that at my age—82 plus—it is no wonder that my resilience has lagged. However, I still live, and having so much before me yet that ought to be done and which I do not like to leave undone, I must evidently husband my strength carefully. '*Venit mors velociter, rapit nos atrociter, nemini parcetur*,' as the Gaudeamus[3] has it. . . . I am especially beholden to you for the good fight you have made on my geological work, which I confidently leave to posterity to judge. The definition and naming of subdivisions of the 'Grand Gulf' interval I willingly leave to quilibet—the interval is there and can be renamed if they want to."

"They have put my graven image in bronze at the door [of the new agricultural building]. That will be to you the main point of interest. One additional thing may interest you, namely, that I shone by my absence, being sick in bed with an attack which took me in the nick of time. Loughridge read my speech and did it well and most of the public knew not Joseph from his substitute. . . . You, at least, were not sick when Smith Hall was inaugurated—*quod bonum, felix, faustumque sit.* But it has been Kismet with me every time a climax came."

The Doctor's own estimate of his scientific work is given in part above in connection with his 1860 report and in part in the following quotation from a recent letter:

"In reply to your request to have me mention the work of my life that I set most store by, I have jotted down '*das mais gloriozas fazanhas*,' as the Portugee would say, among my multitudinous doings."

"With my geological work you are familiar. For the agricultural, most of which has been done on the Pacific coast, . . . I have gone somewhat more in detail. . . . In the matter of direct soil examination, as you know, I have followed David Owen and Robert Peter; but the need of physical analysis becoming obvious, I added that to their procedure. My work in Mississippi gave me only a very one-sided idea of the subject; it opened out when I came to the arid regions, and only assumed its real significance in that connection. Then I recognized its bearing on the history of civilization, which flourished in Assyria when the barbarous Germans and Saxons were still warring in their forests, while living in caves." [4]

"My work in the Mississippi delta mainly caused me to be made a member of the National Academy, and that on arid countries and soils brought me a gold medal from the Munich Academy and a semi-centennial diploma ('*iterum contulimus*') from the University of Heidelberg. So I have special reason to prize these things and what bears on them."

"My continuous agitation for agricultural instruction in the public schools and the popularization of rational agriculture, together with the broad instruction personally given, have given me a somewhat extraordinary popularity in this State."

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[3] German students' song, beginning: Gaudeamus igitur Juvenes dum sumus.

[4] Causes of the development of ancient civilization in arid countries. North American Review, September, 1902.

In his address at the memorial services in honor of Doctor Hilgard, January 30, 1916, Prof. E. J. Wickson said:

"But great as were Hilgard's services to educational science and policy, it is probable that his achievements and influence in agricultural research in the United States will be counted greater. Even if we disregard the incalculable value in his assumption of the agricultural point of view in connection with his geological work in Mississippi, and count his services from his beginning in California, he still stands as the founder of American institutional research in agriculture, including both laboratory and field work."

On same occasion Doctor Loughridge, his life-long companion and friend, said:

"The mind and hand of Professor Hilgard were never idle and, while engaged in solving soil problems in relation to soil fertility and plant life, he was ever on the alert for new ones. The results of his activity are shown in the hundreds of published articles in the experiment station reports, outside journals, both foreign and domestic, government publications, etcetera. In 1906 he published his large work on soils, comprising about 600 pages, and regarded by him as a summary of his life work on arid and humid soils.

"His broad and thorough scientific knowledge, his great work on soils, and his valuable publications brought him not only a world-wide fame, but many honors, among them the degree of LL. D. from the universities of Mississippi, Michigan, Columbia, and California; the Liebig gold medal from the Academy of Sciences, Munich, Bavaria, 'for important advances in agricultural science'; other gold medals from the expositions at Paris, Rio de Janeiro, and Saint Louis; membership in several scientific societies, among them the National Academy of Sciences and the American Association for the Advancement of Science, in which he was made a life member just before his death. In 1883 he received the offer of Assistant Secretary of Agriculture from President Harrison, and leave of absence was granted by the board of regents of the University; but, much to his regret, health conditions compelled him to decline it. In 1903, the fiftieth year after graduation, he received from the University of Heidelberg the semi-centennial diploma reconferring the degree of Ph. D. in recognition of distinguished services in the sciences of geology and agriculture. Only one graduate besides himself has ever received this signal honor."

In reviewing the career of Doctor Hilgard, one is impressed with the fact that from the very first of his scientific activities in Mississippi the subject of the soils has engaged his attention, and that he has persistently followed that thread in all his later work. As one of the most recent of the geological formations, the soil must be considered in its geological relations in any official geological report; but on account of the intimate connection between the soil and the organic life of the land, and especially in its relation to all human activities, the supreme importance of the soil is obvious. These facts were in the mind of Hilgard when, in his first geological report (1860), he devoted half of the report to the geology and half to the soils in their various relations—that is, to agriculture.

Since the soils are derived from preexisting rocks, the study of these rocks must precede the discussion of the soils derived therefrom. Doctor Hilgard has recognized this, and the accuracy and thoroughness with which he has described the geological formations of the Mississippi embayment are evidenced by the fact that subsequent work of geologists in this region, while adding details and filling out some of the outlines laid down, has not necessitated any fundamental change in the geology as depicted by Hilgard in his 1860 report and in his published essays.

As Professor Wickson has said in this connection, Hilgard has demonstrated his power in research and exposition by exalting the State of Mississippi into the first rank of the States which knew their geology to the very bottom of it, and has advanced Mississippi even beyond others of its rank by tracing its soils to the rocks whence they came by ice, wind, and water.

His outlining of the great Mississippi embayment and his recognition of the axis of this embayment as a line of maximum oscillation in late Tertiary and early Quaternary times and his explanation of the accumulation of Grand Gulf and Lafayette sediments in connection with these oscillations must stand to his credit in any estimate of his purely geological work. His recognition of the Cretaceous ridge or backbone of Louisiana and its connection with salt, sulphur, and petroleum occurrences was an achievement of the first importance, as was also his study of the exceptional character of the Lower Mississippi delta, and of the mud lumps, which brought recognition from the National Academy of Sciences, as he has stated above.

Through all this purely geological work, which of itself would have placed Hilgard in the foremost rank of the geologists of his day and generation, the thought of the soil, its nature and characteristics, its relation to forest growth and to cultivation, dwelt constantly in Hilgard's mind, as may be seen in the prominence given to it not only in his first report and in his published articles before he went to California, but also in his numerous official reports of the Department of Agriculture of the University of California.

The chemical analyses of the soils considered in connection with their physical properties, their natural forest vegetation, and the corresponding cultural experience have been consistently carried out by him, as elsewhere stated, with the result of establishing their utility in the *a priori* determination of their adaptation, permanent value, and best means of cultural improvement.

His special study of the physical characters of soils began in Mississippi with the examination of the soils and subsoils of that State with the aid of a "churn elutriator" of his own invention. His investigations of the flocculation of particles in the soils under varied conditions explain many of the peculiarities of soils under cultivation. His further studies in California of the soils of arid climates, of alkaline soils, and the methods of their improvement and reclamation, all go to make up a total of achievement seldom attained. The combined results of these studies find expression in his great work on soils, published in 1906, his "swan song," as he was wont to call it.

That Hilgard was a lifelong student and an untiring worker was well known to all who knew him; to those who knew him not in person these qualities are shown in the long list of published articles to his credit. Such industry insures attainment of the objects proposed, which means success in life. Fortunate is the man who is permitted to witness his own fame; and by such standard must we deem Hilgard fortunate, since he lived to see his life work recognized and appreciated at its full worth by his peers in every land.

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[5] Prepared by Doctor Hilgard and revised and enlarged by Dr. R. H. Loughridge. Professor Hilgard, deeply interested in all branches of science, was a profound thinker and energetic investigator, especially in agriculture, geology, and botany, and a constant contributor to scientific and other periodicals up to a short time before his death, some of his articles even appearing after his death. It has been an almost impossible task to secure a copy of each article and to complete the bibliography which he had begun, for his contributions are to be found in the scientific, agricultural, and other journals of almost every civilized country.—R. H. L.

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(*c*) The production and uses of cottonseed and the cottonseed oil industry.
(*d*) Soil investigations: Introduction to the description of States.
(*e*) General features of the alluvial plain of the Mississippi below the mouth of the Ohio.
(*f*) Report on the cotton production and agricultural features of the State of Louisiana. With two colored maps.
(*g*) Report, etcetera, of the State of Mississippi. With two colored maps.
(*h*) Report, etcetera, of the State of California. With two colored maps.
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Frank A Hill

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MEMORIAL OF FRANK A. HILL

BY BAIRD HALBERSTADT

Marked ability; wide experience in the geology of coal, coal mining, and business; keen perception and sound judgment; kindly frankness; absolute truthfulness; loyalty to employer, employee, and friends alike; devotion to his family; kind and sympathetic consideration of the feelings and views of others, and intense patriotism were the striking characteristics which made it possible for Frank A. Hill, throughout his life, to command and maintain the respect and esteem of all with whom he came in contact.

Mr. Hill, whose death occurred at twilight July 13, 1915, at Pottsville, Pennsylvania, was born at that place on January 30, 1858. He was the son of the late Charles M. and the late Maria G. (Ayer) Hill. He came from a family that had long been identified with the mining of anthracite, his father having been for many years actively engaged as an operator and superintendent, operating the Oak Hill and other large collieries in the southern anthracite field.

Mr. Hill was educated in the private and public schools of Pottsville, graduating from the high school of that place in 1875. His cherished desire for a collegiate education could not be gratified, and at the age of seventeen years he entered the employ of the Philadelphia and Reading Coal and Iron Company as a chainman on its engineer corps, under Gen. Henry Pleasants, an eminent civil and mining engineer. With this company he remained for six years, steadily advancing to higher positions. On the organization of the anthracite district of the Second Geological Survey of Pennsylvania, Mr. Hill was appointed an assistant to Mr. Arthur W. Sheafer, Assistant Geologist, who was in charge of the field-work under Mr. Charles A. Ashburner. Mr. Hill's first geological work was in the extremely intricate Panther Creek district of the Southern Coal Field. Later he was assigned to the Northern Coal Field as Assistant Geologist and placed in responsible charge of the survey of that field, with headquarters at Wilkes-Barre and later at Scranton.

In 1885 he was transferred to headquarters of the Survey in Philadelphia, and the conduct of the work in the entire anthracite region was under his direction. To his tact, diplomacy, and the confidence he inspired among the coal operators and operating companies is largely due the successful conduct and completion of the mapping of the anthracite region. There were many conflicting interests, jealous of each other's success and loath to place in other hands information that had cost thousands of dollars to obtain; yet Mr. Hill, so great was their regard and confidence in him and his assistants, was able to obtain this almost priceless data for the use, in a general way, of the Survey in working out the intricate problems in structure as they were met. Maps, sections, drill-hole records, were, in strictest confidence, placed at his disposal. This confidence was never abused, either by Mr. Hill or any of his young assistants. He was the ideal man for the position, and to him more, perhaps, than to any one else the citizens of Pennsylvania are indebted for the valuable work now at their disposal.

The devotion of Mr. Hill's assistants to him I have seldom seen equaled; it was perhaps never excelled. He was a superior officer, but at the same time he was also a friend, companion, and adviser. To serve under him in the office was a pleasure, to serve with him in the field a delight. He was an inspiration to us for greater endeavor, for no man ever served under him who was not the better for it.

In 1890 Mr. Hill resigned from the Survey to accept the superintendency of the Dunbar Furnace Company, in Fayette County, Pennsylvania. A short time after assuming charge of the furnaces and mines of this company there occurred the disastrous fire at the Hill Farm mine, resulting in the death of thirty-one employees. Mr. Hill's conduct amidst the fire and stifling smoke, hundreds of feet below the surface, in attempting to rescue these men alive, was heroic and called forth the greatest admiration not only from the Government inspectors, but from the officials of the labor organizations and the relatives of the entombed men as well.

Resigning his position at Dunbar in 1893, he was elected Vice-President and General Manager of the Southwest Virginia Improvement Company. With this company he remained until 1895, when he resigned to accept the office of general manager of the Hull Coal and Coke Company, with headquarters in Roanoke, Virginia. With this corporation he remained until 1908, resigning to become resident director of the mining interests of Madeira, Hill & Company, establishing his headquarters in Pottsville. It was this position he held at the time of his death.

In October, 1893, Mr. Hill was united in marriage with Alice Marie Müller, of Joliet, Illinois. To this union were born three children—Frank, Marie, and Alexandrine—who, with his widow and sister, survive him.

As our old chief, Lesley, wrote of Whelpley and Henderson, so I can write of Frank A. Hill, for he was indeed "a man of infinite scope and love in science, poet by divine right, pure hearted and true to every duty to whom as master in youth and friend in middle age the writer has owed what it would be presumption to attempt in words."

To those who knew him best the name of Frank A. Hill was synonymous with all that is best, purest, and noblest in American manhood. Wherever he went he made friends, and as the acquaintanceships lengthened their admiration for him increased. I doubt if he had an enemy in the world. For thirty-five years we were intimate friends, and I can conscientiously say that I believe he was incapable of doing anything that was not honorable. He made the world better for having lived in it.

The funeral services, held at his late residence on Friday afternoon, July 16, 1915, were attended by prominent coal men from all parts of the eastern United States. Interment was in a plot recently selected by himself in the Charles Baber Cemetery, at Pottsville.

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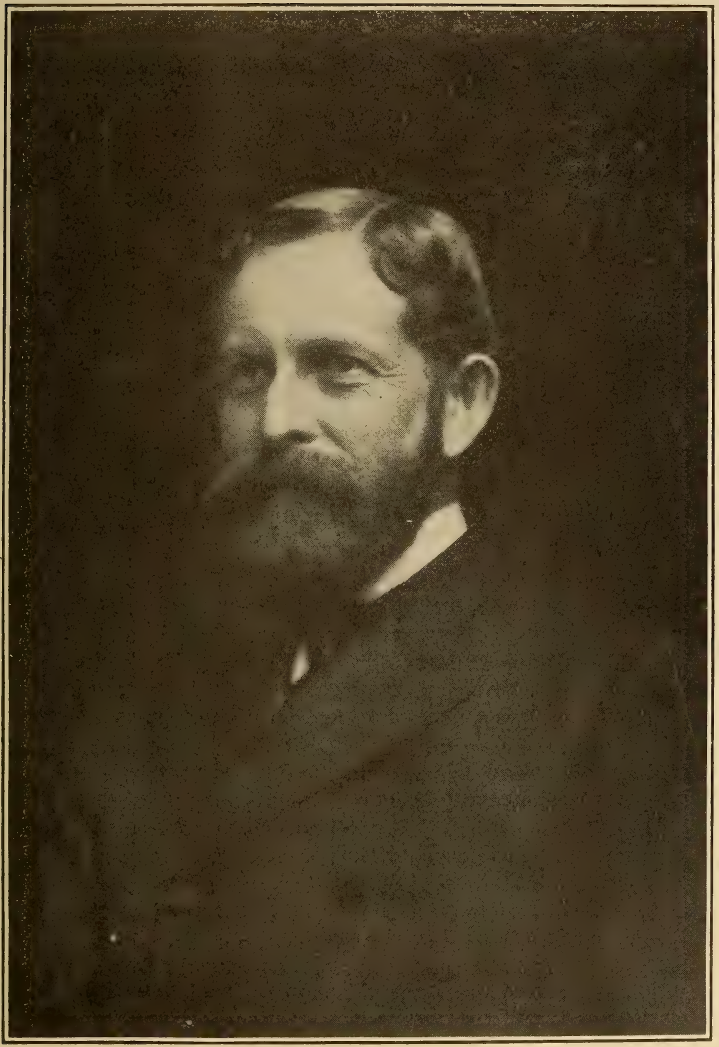
MEMORIAL OF CHARLES SMITH PROSSER

BY E. R. CUMINGS

The untimely death of Prof. Charles Smith Prosser has removed from our ranks another of the original Fellows of the Geological Society of America. He was one of that little company who in 1888 founded this society, now grown so great in numbers and influence. He was also one of the first members of another distinguished society—the Society of Sigma XI—which today has come to exercise a great and increasing influence in that field which Professor Prosser loved so well and in which he wrought so splendidly—the field of university teaching and research. These two circumstances very well typify the two supreme interests of his life, to which he devoted himself with unflagging and unselfish devotion. He was a teacher and an investigator.

Charles Smith Prosser was born March 24, 1860, in Columbus, Chenango County, New York, ninth in the line of descent on his mother's side from William and Elizabeth Tuttle, of New Haven, Connecticut. His father was Smith Prosser, a farmer of somewhat slender substance in the hills along the Unadilla Valley. His New England forebear came from England to Boston in 1635, and later resided in New Haven. For thirty years the Tuttle homestead was the only land owned by Yale College. Savage says: "Of Yale's 10,000 academic graduates (up to 1883), one in 25 is known to be of Tuttle lineage. Its officers, tutors, professors, and fellows are in a still larger ratio, and of its eleven presidents, Dwight and Woolsey ruled the college for more than one-fourth of its existence." From Elizabeth Tuttle, sister of Jonathan, second in the line of descent from William Tuttle, were descended Timothy Dwight, the Edwardses, and many others whose names figure prominently in the genealogies. In 1893 he was married to Mary Frances Wilson, of Albany,



Charles S. Prosser

whose ancestor, William Lawrence, came to this country with the Tuttles in 1635.

At the age of sixteen Charles Prosser entered the Union School at Brookfield, New York, and graduated with the first class in 1879. The following summer was spent in Professor Wait's preparatory school at Ithaca, and he entered Cornell University in the fall, graduating with the class of 1883, with the degree of Bachelor of Science. He began his graduate studies the following year, the first holder of the Cornell Fellowship in Natural History. He now came under the tutelage and inspiration of that master of precise stratigraphic methods, Prof. Henry Shaler Williams, who was to develop the natural aptitudes and tendencies of the boy, already stimulated by the rock ledges of the Unadilla Valley, into the fruitful powers of the fully equipped geologist. He acted as Doctor Williams' assistant in the Devonian laboratory of the United States Geological Survey from 1883 to 1888, spending the greater part of his summers in the field in New York, Pennsylvania, and Ohio.

In 1888 he was appointed an assistant paleontologist on the United States Geological Survey in the division of Paleobotany, then in charge of the versatile Lester F. Ward. He remained with the Survey until 1892, being detailed for field-work in New York, Pennsylvania, Maryland, Virginia, and Arkansas. It can not be said that his experience on the Federal Survey was altogether to his liking, for he was not especially interested in fossil plants, nor was he especially trained in that phase of paleontologic work. The exacting requirements of the work were, however, excellent training, and he acquired during this period particularly that careful technique in the preparation of manuscript and conscientious attention to details which stood him in good stead throughout the rest of his life, and which he imparted in some measure to the younger geologists who received their training under him. This period also brought him the acquaintance of many eminent men and established many a lasting and helpful friendship. He never completely severed his connection with the Survey, but his chief labor was from this time on to be in another field, namely, that of the teacher.

From 1892 to 1894 he was Professor of Geology at Washburn College, Topeka, Kansas. Here began the interest in the younger Paleozoic rocks of Kansas and adjoining States, which was to be foremost in his thoughts for the balance of his life; for always, whatever other problems might temporarily absorb his attention, his mind loved most to dwell on the problems of the Permian. Removal to Union College, New York, in 1894, presently made it impossible for him to do active field-work in Kansas, though he returned several times to his favorite excursions in the sunny State. He had bequeathed the congenial task of collecting the faunas and working out the complicated details of the stratigraphy to a younger man, while his own interest centered more and more on the broader problems of correlation. It was always a source of great gratification to him that through the long and painstaking labors of his Washburn student all of his main conclusions in regard to the age of the Permian rocks of Kansas were finally verified.

At Union College he became interested in the older Paleozoics of the wonderful Mohawk Valley, and found also an opportunity to continue and finally to complete his comprehensive studies, begun at Cornell, of the Upper Devonian. He initiated the studies that have now so completely revolutionized our ideas of the Ordovician formations of the Mohawk Valley. He called attention to the unsuspected thickness of these rocks, and with his students showed that the Trenton of the valley is basal Trenton only, and that the Trenton fauna persists well up into the supposed Utica shale. The years spent at Union College, in spite of its inadequate facilities, were quite the happiest of his life. The whole region—north, south, east, and west from the old Dutch town—is classic ground to the geologist. There was Troy only a few miles away, with its older Cambrian ledges, made famous by the work of Ford; to the north Saratoga, which has served its turn with sundry other names as type section of the Upper Cambrian; to the south, only a couple hours' ride, the Helderbergs, of which Lyell said, A geologist's education is not complete until he has seen this splendid section; to the west all the geologic riches of the Mohawk Valley and its northern tributaries. He established a peripatetic school of geology. Every Saturday, weather permitting (and sometimes not permitting), the new professor of geology and his little flock of students made for the country, to return in the evening tired, dirty, and happy, with their burden of fossils. With his own private library, a small collection of minerals rescued from a long term of innocuous desuetude in the balcony of the old chapel, and such an out-of-doors, he proceeded to stimulate young men to become geologists. In the class-room he was by the common run of students reckoned somewhat dry. He was always passing specimens and huge quartos about and citing references. But in the field he was an enthusiast. He set the student on fire. For the first time in their lives a small group of students at the old college realized what the ultimate sources of knowledge are. They saw that even themselves could add some small contribution to the great body of facts which make up the science of geology. It seems a little thing to those who have spent years in scientific work, but to these boys it was epochal to be brought thus into the workshop of an investigator and to see a science in the making. His method was to bring the student into the most intimate contact with his own studies. He himself was always buried in a pile of specimens and manuscript. He let the students help him. They identified material, hunted out references, copied manuscript, read proof. The students helped with the drawings and colored the maps, and were proud to be of assistance to him in any way they could, and happy, when the report was finally published, to find themselves mentioned in the kindest terms as having aided in its preparation; for he never failed to give full credit to those who assisted him, no matter how humble the person nor how slight the aid. In the laboratory his method was that of Agassiz. He set the student down before a mass of material and expected him to work out his own salvation. He did not stand over a student with constant and insistent suggestion and direction—a method now only too common, with the elaboration of the machinery of teaching and the multiplication of assistantships. He never urged a student to take up geology as his life work. He said to me many times that he did not want any one to become a geologist who was not perfectly certain that he would rather be a geologist than anything else in the world. He did not want to bother with a man who could be easily discouraged. Often he has remarked that the men at Union College cared for pure science. They were not so much interested in dollars and cents as a measure of the importance of the several lines of human endeavor. He appreciated the unworldly atmosphere of the old classical college. His sensitive spirit responded to it as one to the manner born; for he was essentially a man of the cloister. He disliked the hurly-burly of the world.

From 1895 to 1899 he was an assistant on the New York Geological Survey, then still in charge of the veteran geologist, James Hall. In 1898 he was made Chief of the Appalachian Division of the Maryland Geological Survey, and with his collaborators began the long series of Devonian studies of that State which issued finally in the magnificent set of volumes on the Maryland Devonian.

He took with him to Maryland Richard B. Rowe, his first major student at Union College, and the latter, after receiving his degree at the Johns Hopkins University and giving promise of a brilliant career as a geologist, was the first of Professor Prosser's scientific offspring to be stricken by the hand of death. Those who were associated with him then keenly realized how he loved his students. They were his children. He had lost a son.

In 1899 he succeeded Dr. Edward Orton, Sr., at Ohio State University, first as Associate Professor of Geology, and in 1901 as Professor of

Geology and head of the department. In this position he remained until his death.

He was Doctor Orton's personal choice. Those outside of this great university perhaps realized better even than those within its walls the distinction thus conferred on Professor Prosser; for Dana, Leconte, Newberry, and Orton were for many years the most distinguished teachers of geology in this country. The honor was worthily bestowed. He brought to his new position the three essential qualifications of a successful teacher—scholarly productivity, pedagogical skill and experience, and a sterling character.

He at once became identified with the reawakened geological survey of Ohio and resumed active relations with the United States Geological Survey. The latter relationship bore fruit ultimately in the publication of the Columbus Folio in collaboration with Hubbard, Stauffer, Bownocker, and Cumings. The direction of the affairs of a great and growing university department materially increased the burden of administrative work and of teaching duties over those to which he had been accustomed. Nevertheless his productivity showed no decline. He entered with enthusiasm and with his accustomed skill and insight into the study of the stratigraphy of the Ohio formations, and his studies in this new field are comprised in a long series of papers and memoirs, of which the bulletin on the Devonian and Mississippian formations of northeastern Ohio is the most monumental. It is one of the most painstaking and one of the most convincing pieces of detailed stratigraphic work ever done in America. But he paid the penalty for his assiduous and unremitting labors in the temporary breakdown of his health in 1906—a contingency against which his nearest friends had long warned him. I do not think that he ever fully recovered from this collapse. He tugged manfully at his burden, but never again with quite the same vigor. Though he was spared to give ten more years to his university and to science, he was eking out the failing strength of a tired man.

As at Washburn and Union, he raised up about him at Ohio State University a little group of enthusiastic students who are already making themselves known in the field of geologic science.

I desire now to pay tribute first to the *man,* as I have known him for many years, and second to the ideals of scholarly work as he exemplified them.

He was the gentlest of men and the most gentlemanly. As Doctor Clarke has said of him:

> "There never was a more loyal, a more devoted, a more sensitive spirit. His attitude of mind was puritanic in its simplicity and in its practises, and, left

> to himself, he could never suspect another of indirectness or duplicity—a quality of which he contained not a grain. . . . For those whom he knew to be his friends no sacrifice was too great, no defense too vigorous; for them no defection was thinkable. The word of personal criticism seldom passed his lips."

I had known him for years before I ever heard him speak harshly of any one, and then only under stress of the deepest wrong. If he criticized the findings of a fellow-geologist, it was always in the kindliest fashion. I well remember with what infinite reluctance he pointed out the occasional errors of stratigraphic determination into which his distinguished predecessor at Ohio State University had fallen; for every man does occasionally make mistakes. Though the instincts of scientific accuracy in him were stronger even than the warmest ties of friendship, nevertheless he proved that it is possible to correct an error without making an enemy.

He inculcated this spirit in his students, and if any of them have departed from the path on which he set their feet it is greatly to their discredit.

He was a modest man. Sometimes I have thought he was too reticent. I have seen scheming men set ahead of him who were not worthy to unloose the latchet of his shoes; yet his quiet worth shone all the brighter to his students, because, forgetful of self, he gave himself unstintedly to them. Much praise he had for their attainments, but only quiet disparagement of his own. They were always to become famous and to outdo him. It was a relief in this day when we bow the knee to the God of noise to see a man go about his business quietly and unobtrusively. He never confused bluster with efficiency. He never tried to improve his place in the world by clang of bells and blare of horns. But for what was rightfully his he fought with all the panoply of honorable combat.

I quote again from Doctor Clarke:

> "His determinations of fact he was prepared to defend and to claim his title to them, and his high-strung temperament made him revolt when he saw the credit for his determinations complacently or in ignorance absorbed by another. To this he would not become inured, as almost every investigator in science must; it was to him a rape of his golden fleece."

He was a wise man. He gave good counsel, and many a student and many a colleague has sought him out in time of trouble and found his words precious. I wish I might quote from a few of the many letters he wrote to former students—for he never lost track of them—wisely advising them on all sorts of matters.

Finally, since his best years were devoted to university teaching, what were his ideals of scholarly work in the university? He believed that good teaching and scholarly productiveness are inseparable. He believed, with President Van Hise, that "a man who is not a productive scholar will lose in inspirational force as a teacher." He has made this very clear in his address of 1914 as president of the Ohio Chapter of the Sigma Xi; and again, speaking with his colleagues, Professors Leighton and Evans, in that remarkable report to the Faculty of Ohio State University on the nurture of scholarly productiveness, of which President Hall has said that it is one of the most notable reports ever presented to a university faculty. Says this report:

> "It should be recognized as axiomatic that the true note of the university, as distinguished from the college or a group of colleges, is the presence and incessant activity of the spirit which makes for productive scholarship."

He protested against the unending competition of American universities for students. He said:

> "There is no greater fallacy than that all men are born equal, so far as mental ability is concerned. This fact appears to have been frequently lost sight of during recent years, in the effort to secure large numbers of students by those responsible for the administration of our universities."

And, quoting Doctor Mendenhall:

> "The efficiency of many colleges and universities is greatly impaired by the presence of large numbers of students quite unequal to the tasks they are supposed to perform."

Some day—I hope not too late—the American university will learn this lesson.

Professor Prosser saw that the world demands men and women with minds intensively and expertly trained—accurate, painstaking, and persistent. Now, when war has emptied the universities of Europe, as never before, does civilization need the expert, the scholarly man, the productive man.

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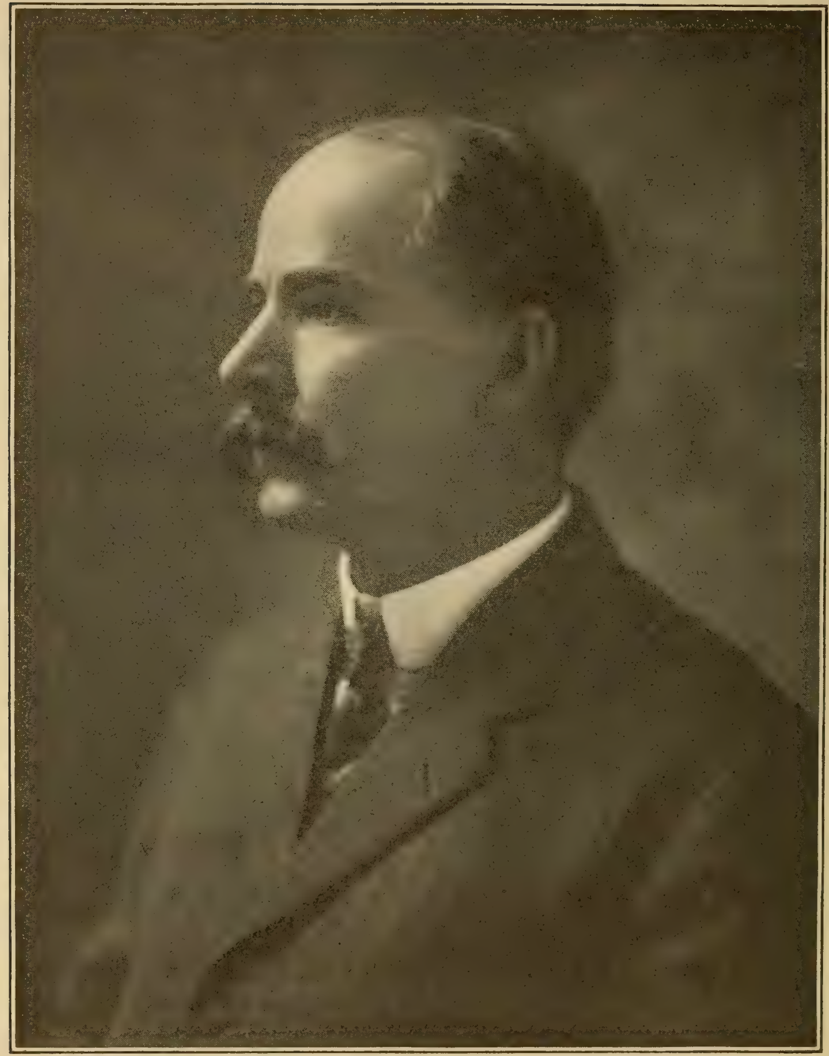

Very sincerely yours –

C. Willard Hayes.

MEMORIAL OF CHARLES WILLARD HAYES[1]

BY ALFRED H. BROOKS

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INTRODUCTION

Hayes's most striking trait was an ability to grasp quickly the elements of a new problem. Trained primarily as a chemist, with the purpose of becoming a teacher, his introduction to geologic field-work was in a region of most complex structure. He soon mastered the problems before him and first became known to the geologic world as a tectonic geologist. Turning from this to physiography, he quickly became a leader in this science. Meanwhile chance opened the field of exploration, and he easily passed from the work of precise mapping to hasty reconnaissance, made under most difficult conditions. From tectonics and physiography he turned to varied investigations relating to mineral deposits, only to desert them for researches directed toward the solving of problems connected with great engineering works.

During the last fifteen years of his life he was best known as an administrator, first of geologic research and then in the business world. In the latter he was confronted with problems which would have baffled a lesser mind.

The scenes of his personal investigations included as widely separated fields as Central America and the Yukon basin, while the scope of his administrative work embraced all phases of geologic research as well as a great industrial enterprise. It is difficult to name any other American geologist who made so conspicuous a success in so many strongly contrasting fields of activity.

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[1] Obituary notices appeared in the following publications: Engineering and Mining Journal, vol. 101, 1916, p. 367; Mining and Scientific Press, vol. 112, 1916, p. 356; Mining and Metallurgical Society of America, vol. ix, 1916, p. 50; Charles Willard Hayes, by David White: Science, vol. xliv, 1916, pp. 124-126.

Ancestry

Charles Willard Hayes, known to his family and intimates as Willard, was born at Granville, Ohio, on October 8, 1858. He was the oldest son and fifth child of Charles Colemen and Ruth Rose Wolcott Hayes. Both parents were descendants of colonial families which migrated to Ohio in the early part of the nineteenth century. He was the fifth generation of the Hayes family in America, the progenitor of the stock having come to Maryland from the north of England in the latter part of the seventeenth century. On his mother's side he was a descendant of the Wolcott family of Connecticut, which was prominent in colonial and Revolutionary history. Through his mother he was closely related to the Winchells of Massachusetts, a family which includes several geologists among its descendants.

Hayes's father was a tanner by trade, a vocation that was only interrupted by his service during the Civil War, when he left his wife and small children to go to the front. In 1868 he moved to Hanover, Ohio, where he established a small tannery. He had made full use of very meager opportunities for education. His son Willard inherited his cheerful disposition, his forcefulness of character, mechanical ability, and his thoroughness in doing any task undertaken.

Hayes's mother was a graduate of the seminary at Granville and had been a teacher before her marriage. Her thirst for knowledge went far beyond the opportunities afforded to a hard-working woman living under pioneer conditions. It was from her that Hayes inherited his strong intellectual tastes, and it was her inspiration which led all her children to seek a higher education. A strong influence in turning Hayes toward a professional career was his older sister, Prof. Ellen Hayes, of Wellesley College, whose inspiration and help guided him throughout his collegiate life.

Boyhood

As a boy Hayes was a sturdy youngster, full of enterprise and without fear, even when very young. His love of outdoor vocations was so marked that it was strange that he ever reconciled himself to his original plan of an academic career based on the chemical laboratory. His favorite pastime as a boy was excursions for collecting, hunting, and fishing, in which his older sisters were his constant companions. An early enterprise of his was the building of a boat, and this, with the gun purchased out of some of his first earnings, provided the means for these excursions. He cared little for the outdoor sports of the average boy, and, though up to the time of his last illness physically very active, never took up any athletics. Most of his life he was too busy for such pastimes, and his physical energy was always directed toward accomplishing some useful purpose.

His character was one of strong contrasts, for, unlike most boys who loved the out-of-doors, he was withal a great reader. This continued throughout his student days and well into his professional career. He was so reticent about expressing opinions on subjects outside of his own specialty that few, even of his intimates, knew how well grounded he was in the classics of English literature. No doubt this background of extensive reading gave him that clearness and forcibleness of expression which characterize his writings. Later in life, when each day's work exhausted his ability for mental concentration, his reading was chiefly with the purpose of relaxation. He did not obtain the relaxation that some brain workers find in scanning serious works on subjects outside his own field of research. This was probably due to his inability to think on a subject without reducing it to its ultimate analysis. In other words, he could not touch on a serious subject lightly for the sake of relaxation.

It appears that as a boy Hayes's interest was not specially directed to geologic phenomena. His home was in a region where the terminal moraine masked the bedrock features. Here the Alleghany Plateau merged with the till plains of Ohio. Yet close at hand were bluffs of Carboniferous sandstone, across which his rambles frequently carried him. His out-of-door interests, like those of most boys, were centered on the more tangible of nature's phenomena. His collections of plants and birds meant more to him than to most country lads, for he not only collected, but he also studied, his trophies. As a result he became well grounded in the local botany and zoology and developed a taste for natural history, which was shown many years later in the jottings of his Nicaraguan and Alaskan journals. Even when his attention was in some measure directed to geologic features by the conversation of a very intelligent young coal miner, who was a frequent visitor at the Hayes household, they awakened no special interest in the science to which he was to devote his life. The same was true during the undergraduate days at Oberlin, where chemistry and mathematics engaged his principal attention. It was not, indeed, until he came under the inspiring influence of George H. Williams at Johns Hopkins that he was attracted to geology. Had other influences during his formative period been active, it is probable that his life's work would have been in a different field. That he would have succeeded in any one of many professions no one who has studied his career can doubt, for he had a remarkable versatility. It was not chance that led him into science, but it was more or less fortuitous that his choice was geology.

It must not be supposed that Hayes's boyhood was passed in following the bent of his own inclinations. What has been recorded above constituted his pastimes in idle moments, which, as he grew older, were all too few, for he was brought up to work. Besides the home duties that fall to the country lad, he spent much time working on his grandfather Wolcott's farm near Granville. Here he gained that love and knowledge of farming that was always a passion with him. When seventeen he spent one summer working in a machine shop in the neighboring town of Newark.

The community of prosperous farmers in which Hayes grew up has transferred to Ohio the intellectual traditions of New England, which there took root. This is made evident by the number of collegiate institutions founded in Ohio during the early history of the State, of which one, Denison University, was in the town of Hayes's nativity. This fact, combined with the more direct influence of his home life, was most favorable to intellectual growth, though the immediately accessible opportunities for education were by no means brilliant.

Hayes began his education in the ungraded school at Hanover, where the standards of teaching were not high. Yet he was, no doubt, there well grounded in the elements of learning. His work is stated to have been steady and successful, and he never complained that any lesson was "too hard," just as in after life he never found any problem too difficult. The elementary schooling was later extended by a term at the preparatory school of Denison University, where he began his preparation for college. At the age of nineteen he entered the subfreshman school of Oberlin College, where his sister Ellen was then a student. His college preparation was more or less broken by the necessity of earning money to continue his studies, but he finally entered Oberlin as a member of the class of 1883.

At Oberlin College

At the time of Hayes's entrance Oberlin College included some 600 students, most of whom were from the Middle West. It is probable that the percentage of these students who had come to college with the purpose of serious work was far greater than that of the undergraduates of the average college today. Hayes entered as a student in the classical and scientific department, but the Oberlin catalogue of 1879 indicates that emphasis was laid on the classic rather than on the scientific courses. Mathematics was the only science taught in the freshman class, while the sophomores were forced to content themselves with physics and botany. It should be said, however, that as a whole the scientific course was broad, including, besides the sciences mentioned above, astronomy, chemistry, zoology, mineralogy, and geology. It would have been advantageous to a student of science if some of the Latin and Greek courses might have given way to modern languages. Hayes was later somewhat hampered in his professional work by the fact that he did not read either French or German fluently, though sufficiently well to use the text-books published in those languages. As a result, his geologic researches were less influenced by European thought than were those of many other American geologists.

Hayes managed to increase his scientific curriculum at Oberlin, both by taking extra work and by obtaining permission to make certain substitutions in the prescribed course. In his junior year, with two fellow-students, he petitioned for permission to substitute chemistry for Butler's Analogy. Of this incident he writes home:

> "There was a great ado in the faculty that we should presume to want another term of chemistry, and that, too, in preference to their precious old Butler. They discussed it and postponed it and discussed it some more, and then, *mirabile dictu*, said we might have it in place of English literature."

Hayes's attitude toward science, as well as that of some of his instructors, is illustrated by a later paragraph in the same letter:

> "In talking with Professor —— after this decision, he maintained that all the ideas involved in chemistry were exhausted in one term's study; that the second term was little else than washing bottles and bending tubes. I could not refrain from telling him what I thought of his conception of science."

He adds, boylike:

> "It made me indignant and gave me a good text for an oration, which I propose to use at the earliest opportunity."

There were, however, other teachers at Oberlin who did not take so narrow a view. Prof. F. F. Jewitt inspired Hayes with an interest in chemistry, and he not only took the full course, but also acted as laboratory assistant. By a curious chance one of his first tasks in the laboratory was the testing of a specimen of phosphate rock; for, as will be shown, he was destined to make phosphate deposits a field of special inquiry.

There can be no doubt that a part of Hayes's interest in the chemical laboratory was due to the facility he had in the use of his hands. Throughout his life he enjoyed working with tools, with which he had remarkable proficiency. This manual dexterity was destined to do him good service in his Alaska explorations and again in his Nicaraguan work. He had rather exceptional mechanical skill and during his Mexican career devised an improvement on a device for loading petroleum tank steamers.

The courses in geology and mineralogy receive no mention in Hayes's Oberlin letters. Only one reference is found to geology, and that is after a lecture by Prof. George F. Wright on a terminal moraine. Hayes then learned that he had lived on one of these moraines, and he writes to his sister:

> "According to Professor Wright, the terminal moraine passes through Licking County, . . . a little west of Hanover. We must look up its track some time and see if we can trace a piece of it ourselves. . . . I want to take a geological trip up Muskingum River. Wouldn't you enjoy such a lark? One summer, you know, we found botany enough in our back lot to keep us busy, and I think there is geology enough within reach of Hanover to keep us busy another summer. What a lot of things are to be seen and studied when one has once had his eyes opened. A favored few seem to be born with their eyes open, but most of us have to have them opened for us."

One of his teachers at Oberlin writes as follows:

> "Doctor Hayes was a good all-round student, standing well above the average of the class in ability, and having, as I remember him, a certain mental poise which generally belongs to a later stage of student life. His work was never hurried and never lagged. A little slow in judgment, he was clear and sure, with an undemonstrative enthusiasm which kept him steadily at work and made him always a pleasant personality in the class-room or the social circle."

Another, who knew him only during his Oberlin days, writes as follows of his recollections, thus proving that many of the fundamental traits of Hayes's character were well developed even as a youth:

> "Hayes was efficient rather than aggressive. He depended for his unquestioned brilliancy on sustained effort rather than on surface brilliancy. He was quiet rather than forward, more inclined to refrain from talking in order to think than to refrain from thinking in order to talk. For this reason, doubtless, he always gave the impression of forces in reserve. . . . He was one to whom a man would go for counsel, knowing that it would be given carefully and wisely, but that he would be the last to volunteer advice to another."

As Hayes supported himself for his entire academic career, he earned money by various vocations during the Oberlin days. It is recorded that, with several fellow-students, he worked at a summer resort in the Thousand Islands, an experience he always spoke of with great pleasure. One summer he also attempted to sell the Encyclopedia Britannica, but his success was only indifferent, as he was not made for a book agent. While an undergraduate, he taught mathematics at the Oberlin preparatory school and was an eminently successful teacher. It was this that turned his thoughts to an academic career, for during his senior year he writes to his sister:

> "Who knows but what I may find my work in the class-room after all. . . . After four terms . . . I should be able to judge whether I have the faculty of imparting knowledge and whether I like the work, so I can do it with my whole soul. Without an undue amount of egotism . . . I think I can answer both questions in the affirmative. . . . What is before me to choose from? Business, journalism, law, the ministry—to all these a decided negative may be given. Medicine I have thought of, . . . but . . . there are some qualities essential to a good physician which I do not possess. . . . Teaching in some form is about all that is left. . . . I sometimes ask myself what I should do with my life if I didn't have to earn my bread. I would devote a good part of it to natural sciences, specially biology and chemistry. Now, if I can follow the same work and earn my bread, . . . are not the chances greater that I will do this work with my whole soul than any other? Again, we only get half the mental blessedness out of knowledge until we impart it to others, so that teaching that which we love ourselves and have enthusiasm for does not seem a burden, but rather a great privilege. . . . I have had an ambition, even before I entered college, to one day occupy a chair of natural sciences, though it seemed too presumptuous to ever realize it."

Hayes was a born teacher, and it was only the enthusiasm for scientific research developed at Johns Hopkins and in the Geological Survey that turned him away from an academic career. Once started on geologic research, he put all thought of teaching aside, though a number of attractive academic positions were offered him.

Hayes went to college for serious study and allowed nothing to interfere with it. In spite of extra studies and teaching, he was by no means a recluse, but entered into the social life of his classmates. In the simple democratic life of Oberlin at that day no social distinctions were drawn; both the well-to-do and poor students mingled in college life. Here, as in later years, Hayes enjoyed intercourse with his fellow-man. His intense modesty, almost diffidence, always gave him a distaste for formal society, but no one entered more heartily or with greater enjoyment into social life among intimate friends.

On graduation in 1883, Hayes had acquired a broad education in the humanities, some knowledge of French and German, an introduction to geology, and other sciences. Most important of all, he had the beginnings of a professional training as a chemist. His plans for further study had to give way to means of earning a livelihood.

A Year of Teaching

It was natural for Hayes to turn to teaching as a means of earning money for further study. Therefore, in the fall of 1883 he took charge of the high school at Brecksville, near Cleveland, Ohio. His first impressions are recorded in a letter:

. . . "I have a fine school—thirty-six wide-awake boys and girls. . . . It will keep my hands full, but the work will not be burdensome because I enjoy it."

A little later he writes:

"I am about distracted by the variety of subjects I have to teach, and it is something of a strain on one's enthusiasm to keep it up all day. . . . I regard it as a kind of crucial test, that if I can teach arithmetic, geography, etcetera, with enthusiasm I surely can chemistry."

While busily engaged in teaching, he yet finds time for studying chemistry, for he writes of reading Cooke's Chemical Philosophy, and his mind is much occupied with his favorite science:

. . . "I will have my appetite for laboratory work well whetted up by this year's work." . . .

His interest in his scholars is unbounded, for he says:

"We do get along capitally together, and I only wish I had more time and strength to give them. Don't you think it is a fine thing to let the wage take its proper place in the background and do the work for the love of it?"

Teaching, study of chemistry, and botanical excursions kept Hayes fully occupied at Brecksville, yet his letters have a note of feeling a lack of intellectual companionship.

"I haven't any fellowship here except with my books and the woods. There are lots of good people here—cautious, shrewd Yankees—with an eye out for the main chance. I am becoming confirmed in my theory of intellectual drainage; the towns drain the country and the cities the towns. I have come on pretty good terms with a few good books this winter, and have found it excellent discipline to have my choice restricted to the books on my own shelf. I think there is something demoralizing in a large library till one has learned thoroughly how to use it."

AT JOHNS HOPKINS UNIVERSITY

While at Brecksville several teaching positions were offered to Hayes, including one at the then newly organized Whitman College in Oregon, but he could not bring himself to give up his plans for graduate work in chemistry. His final choice of universities lay between Harvard and Johns Hopkins. He decided on the latter both because it included only graduate students and because of the presence in the faculty of Remsen, Williams, and others of a brilliant group of investigators that had been attracted by the new institution. Of his choice, his sister, Prof. Ellen Hayes, writes:

> "Willard never regretted going to Baltimore. The three years spent at the 'Hopkins' were certainly among the happiest and richest of his life. He was without care or responsibility; the miscellaneous undergraduate course of a college was replaced by a few closely related subjects, chief of which was the much loved chemistry. He came in daily contact with master minds and he found congenial fellowship with other young men who, like himself, were there in a zeal for knowledge."

In this inspiring atmosphere Hayes developed those high scientific ideals to which he remained true throughout his life.

He arrived in Baltimore in September, 1884, and his almost boyish enthusiasm is shown by his writing:

> "I did not arrive here until late Monday evening, but before I could sleep I had to go around and look at the buildings of the university by moonlight."

Though entered as a student of chemistry, within a month he joined one of Professor Williams's geologic excursions to Pen-Mar—the first of his life, and he was then twenty-six years old. The excursion led to the top of the Blue Ridge, and he writes:

> "I have at last actually been on top of a mountain and looked off. It was grand."

His first work was in chemistry and physics, and much the larger part of his time was spent in the chemical laboratory. He also found time for some advanced studies in German, a language in which he was at that time by no means proficient. His enthusiasm for the work of the chemical laboratory is reflected in his letters. He writes of his first use of the spectroscope:

> "I had always regarded the spectroscope as a kind of myth, though I had seen them and read descriptions of them; . . . but when I saw the Na K and Li lines flash across the screen my skepticism vanished. . . . Those cæsium and rubidium lines came out beautifully, both the blue and the red."

Meanwhile he was active in the Field Naturalists' Club, and said in writing of their meetings:

"It is good to be a specialist, but it is also good to know of other things than one's own specialty."

The study of some octahedral crystals of magnetite leads him to write:

"They give one a concrete conception of the fact that the principles of mathematics are not the device of man."

At the same time he was working in the physical laboratory, determining the wave-lengths of light by means of Rowland's diffraction gratings.

There is no evidence that Hayes had any very definite plans for the study of geology when he went to the Hopkins. His interest in the science appears to have been aroused by the excursions of the Field Club, which brought him in contact with Williams. Previous to this time his taste and training were all for and in the exact sciences of mathematics, chemistry, and physics. It was probably the realization that geology, through mineralogy and crystallography, led back into his own field and his love of an outdoor vocation that brought him to the science the advancement of which was to constitute his life's work.

In November, 1884, he had his first geologic work, of which he says:

"I began today Doctor Williams's lectures on geology and wish I had begun sooner; can't afford to miss them."

And, again, in a later letter:

"We are working now in dynamical geology and are buried deep in volcanoes."

He records his introduction to microscopic petrography:

. . . "It is just the toughest thing I ever got hold of, and I do not propose to be beaten by it."

He still, however, devoted most of his energies to the exact sciences, and his interest in geology was that of the chemist and physicist. After hearing Sir William Thompson's lecture on the rigidity of the earth's crust, he writes:

"I can not say that I apprehend all of his points, but the argument seems good. I am reading some of Fisher's Physics of the Earth's Crust. He takes a very different view from Sir William Thompson. . . . The weakness of the physicists' position is that they are working on inadequate data. . . . When they base such conclusions as they do on the tides, they should have

> very full observations on tides, at a great many places and through a long period of time, and know thoroughly all the influences modifying tidal action, and they haven't these data by any means. Geologists have a very healthy suspicion of 'closet theorists,' for the science has been led on many a wild-goose chase by such parties. Their theories have been very fine, but they have not stood the test of the geologist's hammer. In short, the conditions are so very complex, there are so many variables, that one must look on a formula which would express the whole thing as just a little beyond even Sir William Thompson. When he confines himself to a molecule, no one will object; there are plenty of them. But when he gets to taking liberties with this earth, the geologists must be allowed a word, for it is the only one they have."

This somewhat whimsical comment on the speculations relating to the earth's crust expresses a keynote in Hayes's mental attitude. In all his scientific work it was the seeking of facts and their necessary interpretation that interested him most. That he could grasp the broader problems of geology, requiring a scientific imagination, his publications, notably in physiography, clearly show. He was not, however, inclined to speculate far beyond the established facts. In this lay his strength, but it also involved a loss to geology. Had he, with his fundamental training in the earth's sciences and remarkable power of analysis and exposition, turned to some of the more speculative aspects of geology, he would have advanced the science in other fields than those which he made his own.

He wrote in a letter of February, 1885:

> "My admiration is at present about equally divided between crystallography, as it is being developed by Doctor Williams, and that wonderful carbon chemistry, as the master hand of Professor Remsen unfolds it. The former is almost purely deductive. . . . The relations that come out when the subject is treated logically are beautiful, if they *are* mathematical. . . . Professor Remsen, on the other hand, is in his field an apostle of induction. He insists that every chemical formula which has any value is the result—the focus—of direct lines of experiment and observation, synthetic and analytic. . . . To be sure, this rules out a good many formulas, but chemistry can easily spare them."

In May he is at work, under Doctor Morse's direction, on the best method of the purification of mercury.

> "In the course of the work I came across some very interesting facts, and they suggested a series of experiments, which promise to be very valuable in determining the question of the composition or, rather, methods of combination of the metals in amalgams. No work has ever been done on the vapor tensions of amalgams and metals in vacuo. The pushing out into unbeaten paths is exceedingly fascinating."

In his second year at Johns Hopkins, Hayes was awarded a scholarship in chemistry on the basis of a competitive examination, an honor which he held in as high esteem as the many that came to him in later years. At this time teaching is still in his mind, for he writes, with reference to classical and scientific courses as means of mental discipline,

> "a wooden man can make a course in Greek give discipline, but it requires a born teacher to do the same with an experimental science. . . . But when it comes to a matter that will make him keep his head about him, I will put up a benzine molecule against all comers."

In 1886 the university again honored Hayes by awarding him a fellowship in chemistry. Geology was then an essential part of his course. In June of that year he writes to his sister:

> "I have a scheme for the summer by which I can get some work on my minor geology. . . . It is to work up that glacial drainage problem at Hanover [Ohio]."

This was apparently the first problem in physiography that attracted him. True to his instinct and training for exact observations, he continues:

> "If we borrow a theodolite . . . to locate some contours, it would be a fine piece of work."

The next fall he is intrusted by Doctor Williams with the charge of a Field Club excursion. He puts the students to constructing map and profile, to which he refers as follows:

> "Being responsible for the correctness of a profile adds vastly in interest and benefit to such work. After a certain amount of experience is gained, it is better to strike out alone than to follow at the heels of authority."

Hayes had now (1886) become a member of the inner circle of geologic students. Of this period he writes:

> "Five of us meet there [at Doctor Williams's home] every week and read for a couple of hours and then spend an hour in a social way, with light refreshments. . . . We are reading Lyell's Principles, with side issues that come up incidentally. . . . I have just finished Allen's Darwin. . . . and now I am emulating you in reading Spencer's 'First Principles.' What a satisfaction to get to the bottom of something."

Again, in a later letter:

> "I ought to feel particularly happy tonight, for today I got the reaction toward which I have been working for nearly a year. When I saw my new compound, 'sulphofluorescein,' coming down in beautiful, lustrous, golden-yellow crystals, I wanted to jump up and shout. However, as I am a long way from being out of the woods, I refrained."

While working on this research for his doctorate, he was also working up a collection of rocks from Fernando de Noronha under Doctor Williams.

Though Hayes was deeply immersed in scientific studies, he still found time for other academic subjects. His correspondence shows that he attended lectures on German and English literature and took a course on pedagogics under Prof. G. Stanley Hall. Of him he writes:

> "He is a most delightful lecturer, and it is quite a relief to spend an hour with the humanities after being 'exposed to science' all the week."

A fellow-student at Johns Hopkins writes that Hayes gave him the impression from the start of being a student who was not content to take a statement for granted; but he was always adding something, trying out some reaction, testing some new possibility. He also speaks of the inspiration of the teaching of Doctor Williams, who

> "kept us constantly on the *qui vive* for announcements of new discoveries, and in it all Hayes was one of the foremost students. He [Hayes] was gifted with a keen sense of humor—not a bad quality in a crowd of strenuous young students."

Hayes, with two or three others, made some 5 or 10 grains of sulphinide (saccharine), Doctor Remsen's remarkable discovery. This was the largest quantity of saccharine which had been made at that time. Doctor Remsen was much pleased and "gave us a magnificent offhand talk on sulphinide."

The official record shows that Hayes received his doctorate from Johns Hopkins in 1887, with chemistry as the major and mineralogy and geology as minor subjects. He devoted much of his time in the laboratory to organic chemistry, the title of his doctorate thesis being "Sulphofluorescein and some of its derivatives."

Few geologists have had better preparation in the basal sciences than had Hayes when he left the university. He took advanced standing in chemistry, was trained in the physical laboratory, and completed all the courses in geology given by Doctor Williams. It was Doctor Williams's influence that led him to take geology as a minor, without apparently a thought at that time of making it his life's work. He found no opportunity of studying organic geology, and his lack of training in paleontology, always a source of regret to him, was a handicap in his stratigraphic studies. Strangely enough, he received but little training in stratigraphy, tectonics, and physiography, though these were the branches of geology in which he was destined to attain his highest standing as a geologist. Hayes's broad basal training in science made it possible for him by field studies and reading to fill in the gaps of his academic training.

Appointment to the United States Geological Survey

Up to the time of graduation his highest ambition was to teach chemistry, but chance carried him into an entirely different field. Writing on April 2, 1887, he says:

> "I went down to Washington this morning and had a talk with Mr. [I. C.] Russell, of the Geological Survey, and have decided to spend the summer with him in the mountains of northern Alabama and Tennessee. I go as his assistant at $50 a month and all expenses. . . . If I choose to stay on the Survey I will probably be able to do so; . . . am not sure that I will want to stay permanently. . . . I shall keep a lookout for a place to teach if I don't like this work."

He adds a statement that, years afterward, he was to repeat to many young assistants:

> "There is undoubtedly a chance to rise in the Survey if one is willing to begin at the bottom and work."

Hayes never regretted his choice of geology as his life's work. Once, on visiting a finely equipped chemical laboratory, he remarked:

> "I am not sorry I left this; I like geology better."

Hayes reported to Russell in Alabama about the middle of April, and the next six months were devoted to measurements of an east and west section. This was part of a comprehensive plan to solve southern Appalachian stratigraphy and structure by three detailed sections, to be measured across the entire system. The localities for these sections had been chosen, after careful study, and it fell to Russell to study the southernmost one. It was a laborious piece of work, being done with transit and stadia, and the results achieved were far from being commensurate with the time and energy devoted to it. Russell, who devoted some three years to this work, regarded his time as in large measure wasted.[2] As a training for a young geologist, the work had the advantage of being, in theory at least, precise. In this respect it was probably in advance of most of the stratigraphic and structural work of its day. The impression is gained by a study of the notebooks recording the result that precision of location was, however, gained at the sacrifice of observations over a sufficient area to make it possible to determine structure. Yet it fell to

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[2] G. K. Gilbert: Israel Cook Russell. Journal of Geology, vol. xiv, 1906, p. 664.

Hayes many years later successfully to apply similar methods of accurate instrumental location of outcrops in determining the detailed structures of oil pools. It appears from examination of notebooks that Russell himself undertook the actual measurement of the section, while Hayes's duties were the extending of the mapped area by less precise methods. Hayes's first notebooks show that he applied himself closely to the problem of stratigraphy and structure. It was natural from his training that his mineralogical notes should be more detailed than those usually taken by stratigraphers.

The following winter was to be the first of many spent by Hayes in Washington. It appears that the summer's field work had not yielded enough material to keep the assistant entirely occupied. He was therefore assigned to various duties, including bibliography, mineral statistics, and the installation of an exhibition of fossils at the National Museum. Hayes's intimate association with Russell (for he was a member of his household at this time) was an important influence in developing in the young assistant an interest in the broad problems of geology.

The plan for solving Appalachian structure by detailed cross-sections was reported in 1887 by Major Powell to have been "eminently satisfactory." Those who had actually taken part in the field-work appear to have been less sanguine of the value of results achieved. As a matter of fact, the plan for detailed cross-sections soon gave way to areal mapping, which was found to be the only method to unravel the stratigraphy and complex structure. In 1888 Russell with great pleasure relinquished his claim to the southern Appalachians as a field of research, and it fell to Hayes to bring the work to definite conclusion.

Study of overthrust Faults

Trained both in mathematics and in the exactitude of the chemical and physical laboratory, Hayes applied, so far as practicable, the same precision to geologic field problems. His standards of accuracy, both of observation and record, were more refined than those then generally accepted. Though other American geologists had made detailed geologic maps, Hayes and his colleagues of the Appalachian Division must be recognized as leaders in the modern epoch of precise geologic mapping.

The difficulties of solving the structures and stratigraphic sequence in this field were much enhanced because the standard for base maps was then not high. Maps which would be sufficiently accurate for delineating the larger stratigraphic units utterly failed to serve for the precise mapping undertaken. In other words, the standards of geologic mapping had improved to a far greater extent than had those of topographic surveys.

While many influences were at work which led to the improvement of topographic maps, not the least of these were the concise methods of geologic field-work introduced by Hayes and his colleagues in the Appalachians. Unfortunately Hayes was not personally able to profit greatly by the improvement of base maps, for his field-work was for the most part completed before the new maps became available. Therefore (and this is not generally known) the detailed stratigraphy and structure that he worked out was practically all accomplished without the use of base maps. All observations were located by traverses, and these were combined and the geologic problems worked out independent of any topographic map. For publication the geologic boundaries were then adjusted to the inadequate base maps so far as possible. It should be added that in many instances the topographic surveys were revised before the geologic maps were published. These results were, however, not available for use in the field. The lack of base maps also resulted in delay of publication, and several of Hayes's folios did not appear until many years after the field-work had been completed.

Hayes's first published contribution to geology was a description of some overthrust faults in the southern Appalachians, published when he was 33 years old. It was characteristic of his careful methods of work that one of these faults (the Rome) should have been completely mapped two years before the results were published. The delay was not dilatoriness in preparation of the paper, but because Hayes must satisfy himself as to the correctness of the important conclusions by checking and rechecking the field observations. This method of procedure gave a finality to his scientific conclusions, which was characteristic of his researches as a whole, and therefore they have stood the test of time. Though greater detail of observation and subdivision has led to changes being made in some of Hayes's geologic maps, yet the principles set forth by him have been found to be correct.

No one reading the modest statement contained in Hayes's "Overthrust faults of the southern Appalachians," unless conversant with the previous geologic literature, can realize the epoch-making character of the announcement. The structures there described have proved to be one of the most important clews to the geology of the eastern part of the continent. Rogers, to be sure, had described some thrust-faults connected with close folding; but no one had suspected the presence of the broad, flat overthrusts established by Hayes. Somewhat similar structures had been recognized in the Alps and the Scotch Highlands, and McConnell had then recently found evidence of a thrust-fault in the Canadian Rockies. Hayes's proof of the presence of these great overthrusts furnished the final key to the complex structure of the Appalachians. His exposition was so clear and his facts were so convincing that the interpretation almost at once found general acceptance. The broad thrust-fault type of Appalachian structure so soon became axiomatic that the fact of its being Hayes's discovery was soon lost sight of in geologic literature. The principle developed by Hayes of overthrust faults along planes of erosion also had a broad application in tectonic geology. Of this Willis writes:

> "His patient and accurate field-work led to the discovery of the great, flat overthrusts in the Paleozoic rocks of Georgia and contributed an entirely new interpretation of overthrust faults to the literature of structural geology."

PHYSIOGRAPHY OF SOUTHERN APPALACHIANS

The beginnings of Hayes's professional career were almost coincident with the rise of the modern school of physiography. With his broad interests, he could not but be influenced by this movement, though it was entirely foreign to most of his previous experience. It is clear also that Hayes's Alaska journey, made in 1891, of which more hereafter, had an important influence in developing his interest in physiography. He was, of course, like all geologists, thoroughly conversant with the publications of the older pioneers in physiography, like Powell and Gilbert; but in 1894 it was to the writings of Davis that he made most frequent reference. Some of Davis's first papers dealing with this subject were both presented and published in Washington, and this fact was an important influence in directing the attention of the geologists of the Federal Survey to the systematic analysis of the genesis of land forms. As these papers dealt with Appalachian physiography, they were of special interest to Hayes and his colleagues of the Appalachian division, of which Bailey Willis then had charge. M. R. Campbell, who was Hayes's assistant in 1889-1890, also became a keen student of physiography. The comprehensive plan of working out the physiography of the southern Appalachians appears to have been first proposed by Campbell, but was carried out as a joint investigation. In January, 1893, Hayes writes of this research:

> "At intervals during the past three months, for the most part out of office hours, Mr. Campbell and I have been engaged in bringing together all the available data on the baselevels and development of drainage system in the southern Appalachians."

The results were published a year later as the "Geomorphology of the southern Appalachians," a publication which placed the authors at once in the front rank of American physiographers, this in spite of the fact that it was more or less of a by-product; for both Hayes and Campbell were then chiefly engaged in stratigraphy and structural researches. Though more than a quarter of a century has passed since the appearance of this monograph, it still remains the only comprehensive treatment of the subject. Hayes continued his physiographic studies in the southern Appalachians, and the results appeared in folio and other publications; but his most notable later contributions to this science dealt with Central America.

Geologic Folios

During the first decade of his connection with the Federal Survey Hayes's principal task was areal mapping and the preparation of geologic folios, though during this time he also entered other fields of geology. His executive ability was not severely tested at this time, though it was manifested by his conduct of field parties. Each member of his party had definite duties to perform, and the daily routine was thoroughly systematized, though there were no very obvious regulations or machinery to bring this about. For example, the time for the evening meal was set at 6 o'clock, and a wait of fifteen minutes was made for each man who was late. A scientific assistant was not permitted to take part in camp work unless an emergency arose, when the labor was shared by all. He held that a geologist should not be burdened with unnecessary manual labor, yet when occasion demanded it there were no camp duties which he did not cheerfully perform himself. His camps were comfortable, almost luxurious, and special effort was made to provide as great a variety of well cooked food as the camp afforded. His favorite caution to the cook was, "The best is none too good." There was always one day's rest each week. If rain prevented field-work during the week, the party worked Sundays. As a consequence of this management the party was always keyed up to do a maximum amount of work.

As already stated, the inadequacy of the topographic maps of that day made it necessary for the geologist to prepare his own base. All geologic observations were located by traverses, made on foot, horseback, or buckboard equipped with odometer. The traverses were platted directly in a notebook with the use of celluloid protractor. Contours were sketched, elevations being approximately determined by barometer. Hayes was a master of rapid traverse surveys, which he could make under any and all conditions. I have seen him on his horse in a heavy rain platting his notes and protecting the leaves of the book by holding it directly over his head.

The problems met with during the day were discussed around the evening camp-fire. Hayes had great facility in drawing out a young geologist and finding out his point of view. Though he made the final decision on a problem under joint investigation, Hayes was always ready to listen to interpretations made by an assistant. If, however, he assigned a definite problem to an assistant, he left him to work out his own salvation.

One of the reasons for Hayes's success in his field-work was the admiration he inspired in his assistants. All became his devoted followers, yet his influence did not tend to make disciples, but rather independent thinkers. He insisted that they search out all the facts and then draw their own conclusions. Hayes's wonderful success as an administrator of large affairs was due to the same quality. His policy developed men to their highest capacity and then put them to their best use.

Hayes closed his areal mapping in the southern Appalachians in 1896, though a little supplementary work was done the next year. Unfortunately for the science of geology, the inaccuracy of the base maps deferred and in certain instances prevented the publication of many of the folios which had been prepared at so great a cost of time and labor. On April 30, 1897, he writes:

> "In addition to the folios, I wish to prepare for publication during the coming year a monographic report on the entire area surveyed by myself and assistants in the southern Appalachians during the past ten years."

Some months later he says:

> "My office work has been chiefly on the monograph."

Unfortunately, owing to other assignments, Hayes never completed this monograph, and the results of a decade of intensive study are recorded in only a fragmentary way. Many of Hayes's ideas and the principles established by him were incorporated in the work of others, and this is as he wished it. Hayes always gave freely to his associates and subordinates, for his ideal was results and not personal glorification. This can be illustrated by a personal experience. A junior geologist working as his assistant had opportunity to prepare a geologic paper involving such extensive use of Hayes's unpublished material as to justify joint authorship. The junior was, however, instructed to prepare the article, to use any material he desired, and publish it over his own name.

While the broad plan of quadrangle mapping and folio publication is to be credited to Powell, Gilbert, and Willis, yet in its execution Hayes played an important part. He was the author of number 2 of the series

(Ringold), the first to be published on the standard scale of two miles to the inch. Moreover, he prepared eight of the first twenty-two issued, and as Chief Geologist gave close personal attention to later folio publication. Though the first folios appear crude when compared with those of the present day, yet be it remembered that the mapping therein used was much more refined than most of that which preceded it.

ALASKA EXPLORATION

His intimate association with Russell during the period when the latter was engaged in his northern exploration accounts for Hayes's interest in Alaska, then to the geologist an almost untrodden field. In 1891 Lieut. Frederick Schwatka invited Russell to take part in an exploration of the upper Yukon basin. As Russell was deeply involved in his own field, the opportunity came to Hayes. Up to this time Hayes's geologic studies had been only in the southern Appalachians, and he had never been west of Ohio. Therefore the journey across the continent by the Canadian route was a revelation to him, and his notebook is crowded with observations made from the car window. These were chiefly matters of detail, but they were destined to find fruit in a broad interpretation of continental physiography which came some time later. His interest was specially centered on glacial phenomena, which was new to him as a geologist, though his earlier years had been spent in a glaciated region. His observations were by no means confined to geology, for many facts relating to geography and industry found place in his notebook.

The results of the exploration in which Hayes took such a prominent part have long since been fully presented, but it is worth while to outline its general features, and, above all, to record his personal impressions. The route of travel for his party of three was to Juneau by steamer, where the exploration began. From there Taku Inlet was followed to its head, and thence a route found through the Coast Range by the Taku River. Hayes recorded his impressions on this journey in his journal, his letters, and an unpublished manuscript, from which the following quotations are taken. He thus tells of the departure from Juneau:

> "Our craft was a Tlinket war canoe made from a single cedar log and capable of carrying thirty or forty men. As we disappeared into the fog, with the wild chant of natives keeping time with their paddles, I fancy we must have had a strong resemblance to an old-time war party bent on a foray. Our feelings were decidedly less warlike than a few days later, when our Indians began to show their true character and the depravity of their mulish dispositions."

The ascent of the Taku River proved difficult, but finally the party left the Coast Range behind and emerged in the Central Plateau region. Here Hayes for the first time in his life viewed a broad landscape under a clear atmosphere and wrote of it a delightful description.

> "Pushing on a couple of miles beyond this camp to a high point on the divide, I had a view 'siah illahee.' Away to the westward were the snowy summits of the Coast Range, with an intervening high, rolling plateau, above which projected round domelike summits. The valleys and lower slopes showed the dark green of spruce forests, while a mantle of brownish green moss spread over all the higher land. To the north and south extended the same great stretch of moss-covered moorland, with an occasional bare, rocky peak extending above the rolling surface. Immediately to the east and about 3,000 feet below the point on which I stood was a level valley filled with innumerable small lakes, and to the north occupied by the larger body of water called Aklene, or big lake. Across the valley, about 20 miles away, was an escarpment corresponding to the one at my feet; beyond that a broad, rolling plateau similar to the one we had been traversing; and still farther east appeared the sharply serrate Cassiar Range, white with perennial snow."

Every Alaska explorer has noted the insect pest of which Hayes's description is as follows:

> "Although the snow lay in deep drifts about us and several small lakes were still covered with ice, it was at this high camp that we made our first intimate acquaintance with the great Alaskan mosquito. They are not the coy, coquettish kind with which you may be familiar, but with an appetite inherited from many generations of famished ancestors, they attack any exposed parts with fairly murderous vehemence, and nothing but complete annihilation causes them to desist. They swarm about the head of the unhappy traveler in such numbers that at a little distance his head appears to be enveloped in a dense cloud trailing off behind like the tail of a comet. Many of the Indians protect themselves by covering the face with a thick coating of soot and grease—a practice which does not tend to heighten their personal charm. . . . Without doubt this insect pest will always be a greater hindrance to the development of this country's resources than all other difficulties combined.
>
> "Two days more of weary plodding through the dense forests and deep swamps of the valley brought us to the head of the lake. From this point the Indians were sent back to the coast, and it was with feelings of intense relief that we watched them disappear on the homeward trail and knew that we were no longer dependent on their caprice. Setting up the two portable canvas canoes, after a day's stop in order to get observations for latitude, we continued our journey, turning to the northwest down Lake Aklene."

Tracing the Hootalinqua River to its mouth, the three explorers continued their journey down the Lewis River, already well known to Fort Selkirk. Here a long delay was occasioned by the necessity of securing Indian packers for the overland trip to the head of the White River.

> "After much persuasion, we finally secured seven pack dogs and five Indians who promised to go through with us to the country of Scolai (Copper River), where the water flowed into the sea, and on July 9 our little party left Selkirk and struck out into the great unknown."

The journey now lay to the northwest, across the Yukon Plateau toward the Saint Elias Range. A large glacier had to be crossed.

> "It was curious and pitiful to see the terror with which the Indians regarded the glacier. To them it was full of strange and unknown dangers. And indeed, with its weird, rumbling noises, its yawning crevasses, and the rushing of hidden waters, it is not strange that to their superstitious minds it should appear to be the abode of demons to be shunned or placated. Before venturing on the ice, Jackson stopped to 'make medicine' in order to secure a safe passage, and the other Indians besought us not to speak or make a noise while crossing."

The little party was now close to the base of the range, and here the Indians deserted them, fearful, as is so common with Alaska natives, of entering a region which was out of their hunting ground. Nothing daunted, the three white men shouldered as heavy packs as they could carry and boldly struck out in the snow- and ice-covered mountains in the hope of finding a pass to the Copper River basin. In this they succeeded, and after many perilous adventures among the ice-covered slopes reached a river flowing into the Pacific.

> . . . "It was deemed advisable to exchange our mode of travel for one more expeditious, and near the point where the river turns again to the west we stopped and built a boat. Our tools consisted of a very dull axe and our pocket knives; but with these we hewed out a keel and gunwales from spruce saplings and fashioned ribs from willow poles, lashing the structure together with twine raveled from our pack ropes. Over this frame, which looked something like an overgrown chicken coop, we stretched the canvas in which our bedding had been wrapped and finally smeared on a liberal coating of spruce gum.
>
> "In this craft—the *Forlorn Hope*—we embarked, and in the next half hour had made more progress than in our last day's march. We had also, at the end of the first half hour, gained a large experience in the art of boating. It was necessary to prevent the boat from striking bottom, for every time that happened a hole was torn in the canvas and a patch necessitated. In jumping out to prevent striking, both Mark and I had been thrown down in the water and rolled over and generally maltreated. But when we learned the little peculiarities of our craft her conduct was unexceptionable."

Finally, after running the Nizina Canyon, in which many prospectors, even in well built boats, have since lost their lives, the party reached the Chitina River, followed this to the Copper River, and reached the native settlement of Taral. Here Indians were engaged for the final journey to the coast, which, in a good boat, presented no difficulties, though not without serious dangers. The journey of a thousand miles, much of it through entirely unknown regions, was accomplished without accident and exactly as had been planned. To Schwatka, the leader, must be given all due credit, but the tangible results were almost entirely the work of Hayes. Throughout the journey he not only made a track survey of remarkable accuracy, based on pacing by land and estimates of distances by water, but his geologic record was unbroken. Whether toiling through a swamp, bearing a heavy burden, finding a precarious footing on canyon walls, or shooting the rapids of unknown rivers in a frail craft, his eye was ever alert for geologic and geographic facts. He was the pioneer in Alaska surveys in substituting precise observations, accurately located, for the random notes of the old-fashioned explorer. It was characteristic of Hayes that, leaving the detailed mapping of his own special province and trained only in this class of field-work, he at once adapted both his mental attitude and methods of investigations to the work of rapid exploration. Throughout his professional career he showed the same mental quality of almost at once grasping the essentials of new problems in fields which had previously been entirely foreign to him. Thus he passed directly from the chemical laboratory to tectonic geology and almost at once mastered physiography. These were left, in turn, for the fields of exploration and applied geology. In all these branches of his chosen science he showed the master hand.

This exploration led to an understanding of the larger bedrock features of the region. An incidental contribution to science was the tracing to its approximate source of the white volcanic ash so widely distributed in the upper Yukon basin. He was also the first geologist to describe the occurrence of copper in the region traversed by him. By far the most important result of this study was Hayes's classification of the larger physiographic features. This, only in part elaborated in his paper dealing with this expedition, was more fully set forth in a later publication, but never published in graphic form. The broad grasp he had on the problem is shown by the fact that though at the time of his classification much of Alaska was unknown, yet the physiographic subdivisions he proposed have been but little modified after twenty years of surveys and investigations.

The knowledge that Hayes gained by his northern journey was a very important element in the success of Alaska surveys begun several years later. His familiarity with the physical conditions of travel and the broader features of Alaska's relief and geology made the National Survey rely in large measure on his counsel. It is not generally known that he planned several of the earlier expeditions and would undoubtedly have been placed in charge of the Alaska work in 1898 had he not then been in Nicaragua.

WORK IN NICARAGUA

Hayes's next assignment was to carry him into an entirely new field of research, both geographically and geologically—the latter because it was the application of geology to engineering problems, then a comparatively new field on this continent. When the Nicaragua Canal Commission was organized the president, Adm. John G. Walker, requested Dr. Arnold Hague to recommend a geologist. Doctor Hague, after taking into consideration the character of the investigations, recommended Hayes as the best man for the position. A conference between Hayes and Admiral Walker soon settled the matter, and Hayes was detailed to the position in December, 1897.

It was characteristic of the man that he should make no protest against the assignment, though it necessitated his leaving home when one of his children was but a day old. Throughout his career he allowed no personal sacrifice to interfere with the carrying out of his official duty.

Hayes's field orders from the Commission charged him both with the duty of making the borings necessary to the engineering works and also of making general physiographic studies. This work made a strong appeal to Hayes, both because it called into play for the first time his latent executive ability and because it afforded opportunity to utilize his mechanical bent of mind. Above all, he welcomed the assignment because the field presented a fascinating physiographic problem. His first duties were remote from the field-work of his previous experiences. The organization of drilling parties, distribution of supplies, and the designing of drilling equipment were both absorbing and difficult, specially since on landing in Graytown he became ill with fever. In spite of this, within ten days of the time of landing he was engaged in building his first camp and in selecting the site for his first drilling operations. His journal records the daily routine, moving men and supplies, building camps, and other varied duties. With it all are recorded geologic observations. Hayes also found time to note many facts relating to the land, its vegetation, animal life, and people. The incessant rains constituted another hindrance to progress, but a careful search of the circumstantial account of the daily routine utterly fails to reveal any note of discouragement. Here, as in all other phases of his varied career, Hayes showed that buoyancy and enthusiasm which carried him through all difficulties.

His field of operations was in time extended over the entire length of the canal route, where he had a number of parties engaged in drilling along the zone. Hayes was almost constantly traveling during the nineteen months devoted to this field. A few extracts from his journal will give a conception of his life, though most of the writing is a record of his geologic observations:

> "This morning resumed the building of camp. Detailed gangs of workmen for particular tasks, as cutting palm leaves for thatch, poles for flooring and rafters, and vines for lashing. . . . I start with O'Reardon south from camp, running a traverse line. In crossing a deep creek O'Reardon slipped off log and went completely under. I could see his pink shirt through the clear water and, reaching down, pulled him out. He was a comical sight, but showed good nerve and held on to the gun he was carrying. . . . During trip saw following animals: Lots of monkeys, two alligators, one over ten feet long; a manitee, a sloth hanging on a limb over the river, an iguana, a lizard in a tree-top, three feet or more in length; also a large number of cranes, herons, and other birds. . . . Find a rubber tree on bank; tap it, and O'Reardon covers his canvas compass can, making it thoroughly waterproof. . . . Make a map of drilling operations on both sides of river; measure and level up all the holes and locate two new ones. . . . We are roused by the steamer whistle before daylight and pack up hurriedly in the gray dawn. Have coffee and bread on board—the latter a great luxury. . . . Get a dugout canoe and two natives and go back to the mouth of the San Francisco. . . . We cook breakfast—coffee, baked beans, and hardtack. . . . The men were alone under the tarpaulin. One of them claimed he saw a panther (tiger he called it) and raised the alarm. All set up an agonized screeching. . . . Found the men pale with fear. During the remainder of the night A. fired his revolver at frequent intervals, claiming he could smell the beast. . . . This party lives on a raft, on which a tent has been erected. It is rather close quarters for four officers and twelve mozos. I have to swing my hammock between two posts when I make them a visit. We had quite an exciting time coming over the rapids a few days ago. This was not so difficult as stopping in the swift water below. We broke several lines before we succeeded in mooring the 'ark' to the bank. It is not quite as much of an ark as it was before they disposed of most of the livestock, and now have left only one dog, one monkey, and two parrots."

Hayes's difficulties were not only due to physical obstacles, for he records in his journal:

> "The men having been paid off today have been loading up, and after supper begin to raise Ned. B. gets silly drunk, and after quarreling with L. comes weeping to my tent and threatens to drown himself. Says everybody in camp has combined to injure him and wants to leave. He presents an indescribably ludicrous appearance. . . . We reach the San Francisco and find it swollen with a strong current. Have a hard pull coming up, . . . and find the only way to make progress is to do all the steering myself. . . . We reach the

big tree below camp and have a hard struggle getting over. . . . We get stuck on all the snags, but by good luck and bull strengh finally reach camp. I hustle around and get places for the men to sleep. They are entirely helpless in an emergency and the officers are almost as bad. Everybody disposed to grumble, and I have to blow them up and put them in good humor or on their mettle. . . . F. drives pipe 30 feet before taking sample and would go on indefinitely if not stopped. Appears to think object is to get a hole in the ground rather than to find out what he is driving through. I stay with him all the morning and keep his record. . . . We reach M.'s ranch just at dusk. . . . Sleep in dining-room. The house is surrounded by piazzas, and these are occupied by many dogs, while a large brood of pigs lives under the house. The dogs get excited at intervals during the night and make frightful racket, while the pigs have their own differences to settle.

"This morning . . . heard a noise in the high grass and, turning, saw a 'mountain cow,' or tapir, quietly feeding about 15 feet from me. After getting a good look at beast, I fired at it with my revolver and it went crashing off into the bushes. . . . Spent the day building raft, . . . practically ready for use. It is 14 x 16 feet, with a recess at one end for the drill. We finished it, fitted anchors, set up the drill, and then started to our station. A boat crew carried an anchor as far as possible, the raft was swung out on this, and when at rest the boat carried out another anchor. In this way we worked out into midstream and lowered the raft gradually to the line of the dam, and then drove down two piles on either side. . . . Continue up the creek with increasing difficulties. Kill an alligator 9 feet long with an improvised spear made by lashing a machete to a pole."

While engaged in this work Hayes had his first experience with revolutions, a condition with which he was destined to have much close contact during his Mexican experience. In February, 1898, he records that:

"We hear various rumors of a revolution. One is that they have seized the boats on the lake and another that they have captured Rivas."

At Granada some time later he notes that:

"A rabble of generals and barefooted soldiers come aboard (the river steamer) and raise Cain most of the night. . . . The town is filled with soldiers—a ragged mob. Business is at a standstill and most of the well-to-do men are 'emigrados.' . . . There have been nine revolutions since the liberal party came into power five years ago."

He, however, writes home reassuringly:

"Also you must not worry about any reports you see in the papers regarding revolutions. They are harmless, but very annoying, as the Government has impressed all the steamers and we have great difficulty in getting supplies up into the interior."

Though holding only a comparatively subordinate position, Hayes's strong personality and quick insight into the large problems gave him great influence with the Commission. This fact can be read between the lines of Hayes's very modest account of his work, as recorded in his journal, and is also shown by the numerous references to results of the geologist in the report of the Commission. It is perhaps the first instance on this continent where the plan for a great engineering project found its principal support in the arguments offered by a physiographer.

The valuable public service rendered by the Nicaragua Canal Commission and its employees was, with the selection of the Panama route, for the most part in vain, except insomuch as it contributed to a better knowledge of a little known region. In this Hayes's contribution led all the rest. His close analysis of the physiographic history of the Nicaragua Canal was perhaps his most notable contribution to geomorphology. It stands today as the best treatise on the physiography of any part of Central America. Hayes's writings were all clear and concise, but his Nicaraguan was a masterpiece of physiographic exposition. Though he gave no attention to coral reefs, yet he must be credited with being the first of the modern school of geologists to apply physiographic criteria to a study of shoreline history in a coral reef province.

An incidental contribution of this investigation was a geologic map of much of Nicaragua. In the preparation of this he was much hampered by the physical conditions of the province and by the fact that his administrative duties gave him relatively little opportunity to extend his operations away from the Canal Zone. Hayes was himself pleased with the results of his Nicaragua work. Soon after his return he writes to Russell:

> "You are right in supposing that I am glad to get out of the woods. The three months for which I went down stretched out to a seemingly interminable length. . . . On the whole, it was the most profitable field season I have spent, not excepting the one in Alaska. I have not had much time to look up the literature, but so far as I know Nicaragua is practically a virgin field to the geologist. . . . It is remarkable how much geomorphology is crowded into the narrow strip of country separating the two oceans and how completely it has been overlooked by the many engineers who have visited the region."

Hayes's eminent success as geologic adviser in engineering works was one of the principal reasons for his assignment to similar duties in the Panama Canal Zone. The plan of a geologic examination at Panama seems to have originated with the Hon. James Bryce. On his return from South America, by way of Panama, he suggested to President Taft the advisability of scientific surveys, especially geological, of the Canal Zone. As a consequence, in 1910 Hayes was detailed to the War Department for investigations on Panama, with instructions to report to General Goethals. Though he was able to devote only a month to this work, yet this sufficed for him to grasp the salient features of the problem. In a brief report he pointed out the causes of the landslides which were then threatening the Culebra Cut and suggested means for overcoming the difficulties. Hayes also outlined a plan for further investigations and recommended continuous observations as the work progressed. The principles he announced relating to the causes of the slides have been verified by all subsequent investigators.

Hayes made one other geologic excursion into the Caribbean region. At the second occupation of Cuba, General Wood, Military Governor, owing to a suggestion of Dr. David T. Day, made a request for a geologic reconnaissance of the island with the purpose of determining its mineral resources. Hayes was detailed in charge of this work in 1901, assisted by T. Wayland Vaughan and Arthur C. Spencer. Hayes was able to devote only five weeks to the field-work, while his assistant spent some three months in Cuba. Before the end of the year a report on the geology and mineral resources of Cuba—the first of its kind—was submitted.

Economic Geology

During the first six years of his professional work Hayes devoted relatively little time to the study of mineral deposits. When in 1893 the modern epoch of the National Survey's activity in economic geology began, it fell to Hayes to study the Tennessee phosphates, and in the following year the bauxite deposits of the South. In this field he made his first direct application of chemistry, to the study of which he had devoted so many years of his life. As was to be expected, he soon became the leading authority on the occurrence of bauxite and phosphate.

In his description of these deposits he presented not only the facts and interpretations in regard to occurrence and origin, but also made quantitative estimates of reserves. His was, therefore, among the first reports of the Federal Survey to treat of mineral resources in a quantitative way. Later, when under the stimulus of the conservation movement, a census of the mineral deposits of the country was called for, he was far better able to supervise the work in his capacity of Chief Geologist, because it was but an extension of his own work.

The importance of Hayes's work in economic geology, as well as his administrative ability, was recognized in 1900 by placing him in charge of the newly organized section of non-metalliferous resources. For the next five years Hayes continued to give personal supervision to this work in spite of the fact that he had meanwhile assumed other heavy administrative duties. This was a period of enormous expansion of the non-metalliferous economic investigations of the Federal Survey, especially in the investigation of mineral fuels. The broad plan of making a detailed survey of the coal and oil fields of the United States is essentially that of Hayes. His immediate attention on assuming the new position was directed to making available the existing information about the coal fields.

During the first dozen years of its existence the Federal Survey had investigated many of the coal fields of the United States. A much larger amount of work had been done by State geological surveys. By these various agencies a large amount of data had been accumulated, but this was scattered through many publications, for no summary had been made since that contained in the Tenth Census, prepared under the direction of Clarence King. Meanwhile the coal-mining industry had grown apace and the public had become deeply interested in the question of mineral reserves. These conditions made a new summary of the data relating to coal desirable, and to this end a plan was formulated, in cooperation with E. W. Parker. It contemplated the enormous task of summarizing not only the geology of the coal fields, but also the statistics of production, together with a discussion of economic conditions. The first of these tasks fell to Hayes. Within a year manuscripts describing all the coal fields, prepared by ten authors, were submitted. These, when printed, formed a volume of nearly six hundred pages. Hayes not only supervised this work, but himself prepared two important chapters. Summary reports on a number of other mineral deposits were also prepared under Hayes's direction.

Meanwhile, in 1902, Hayes first turned his attention to the geology of petroleum. This was a field where his training in detailed structure was to find its most important application. His personal investigations were in Louisiana and Texas, but he also gave close attention to the California, mid-continental, and Appalachian oil fields, where other geologists were working under his direction. It was under his guidance that the refinements of detailed stratigraphic and structural studies were first to be applied in a large way. Mining engineers and geologists had, of course, applied similar methods to small areas before Hayes introduced them into the National Survey. It remained for him, however, to show that detailed structures could be worked out over large areas without an inordinate expenditure of time and money. It was his success in the locating of oil pools that led to his being called later to the important Mexican position. Hayes closed his career as an investigator by his researches on oil. It is a great loss to the science of geology that conditions never permitted his putting on record the results of his researches on the geology of petroleum, which occupied him for much of his time during the last fifteen years of his life.

CHIEF GEOLOGIST

Hayes's executive ability was first recognized by the National Survey in 1896, when a plan for a reorganization of the topographic branch was considered which contemplated his being made Chief Geographer. Probably fortunately for geology, this plan was not carried into effect, though had it been, physiography would undoubtedly have been the gainer. As already stated, in 1900 he was placed in charge of the Survey's work in certain economic fields. Two years later he was given full charge of all the geologic work of the National Survey in the United States. This was followed in 1905 by putting under his administrative control the geologic branch, including the divisions of Geology, Mineral Resources, Chemical and Physical Research, and Alaskan Mineral Resources. Though he was then in fact, though not in name, the Chief Geologist, this office, previously held by Mr. Gilbert, was not revived until 1907.

The heavy duties as administrator of the geologic branch left him little time for his own researches. Though he never complained, the relinquishment of his own scientific work was always a matter of great regret. He writes on this subject:

> "I fully appreciate your feelings in regard to giving up field-work, but that is one inevitable consequence of accepting an administrative position."

One important compensation was the opportunity the new position afforded to see something of the West. Previous to 1902, except for the Alaska journey and the Central American work, his investigations had been entirely confined to the eastern half of the continent. Of his first journey to the West he writes:

> "I was exceedingly interested in what I saw of California and the Southwest. It was all new to me, a genuine revelation, particularly the desert topography. . . . I think it will put me in a position to plan work in various parts of the West much more intelligently than heretofore."

Having accepted the responsibilities of the geologic field-work, he threw himself into it wholeheartedly and regarded it as his principal duty to help others. On one of his journeys to the West he writes:

> "I had several objects in coming out here; among others, to learn something of the geologic problems involved, to get better acquainted with the men, and to see how the work is actually being done in the field. . . . I feel that I

have at least a rudimentary knowledge of the post-Paleozoic geology from Musselshell south through to Big Horn basin and can listen to the discussions next winter with some degree of comprehension."

Though his interest in geologic problems was always present, yet he believed that it was his special mission to study the field-workers themselves.

> "I have come to know some of the men better than I could during many years in Washington. X. is surely making good. He has a genius of organization and the handling of men. . . . Both —— and —— are doing good work and are very enthusiastic. . . . Knowing the men, you will not be surprised that I urged attention to detail on —— and speed on ——. . . . Of —— I have serious doubts. . . . Some things came out during our conference . . . which makes me wary of him. . . . I think his party should be watched most closely. Of the others I have no fears whatever."

Hayes's keen interest in the individual is typified by the following extract from a letter to a young assistant:

> "You are very fortunate in your summer's work, and I am sure you will make the most of your opportunities or I would not have recommended the assignment. Keep wide awake and your eyes open. Do not for the time being think about the past or future, but put your whole soul into the day's work. Many of the days will seem long and tedious, but they must be taken with the interesting and exciting ones."

It was this kind of personal interest in his associates which made Hayes so successful an administrator, for he inspired absolute confidence and loyalty in his subordinates. In dealing with men he was always direct, sometimes to the extent of bluntness. Even those who differed radically with him on policy never doubted his motives or the honesty of his convictions. He in turn showed the same loyalty to his superiors and to the organization which he served that he found and expected in his assistants.

While there were not a few among his associates who differed with Hayes on questions of policy, there were none who did not recognize his scientific ability and qualities of leadership. When Doctor Walcott resigned, Hayes was among his colleagues of the Survey almost the unanimous first choice for the directorship, and no one gave him stronger support than Dr. George Otis Smith. Hayes made no canvass whatever for the position and, in fact, would have accepted it, had it been offered, only with great reluctance, for he dreaded the responsibilities. Before any appointment was made he assured me that he would serve loyally under any one of several geologists that he named. He was true to his word.

If he felt any injustice had been done in that long service had not been recognized, it was effectually masked, even to his most intimate friends. Certainly no one served the new Director more loyally than did Doctor Hayes.

Hayes had enormous capacity for work and was systematic and thorough. His administrative success was largely due to this, to inherent qualities of leadership, and to a genius for applying what is generally called common sense to any problem that arose. His fairmindedness is illustrated by an incident which happened while he was Chief Geologist. A much younger man had in a public meeting attacked rather viciously some of Hayes's earlier geological work and later apologized by letter. To this Hayes replied in part as follows:

> "I have no patience with the infallible geologist, who never makes a mistake, nor the one who is unwilling to admit a mistake when it is pointed out. I can therefore harbor no hard feelings whatever for anything said at the Geological Society meeting."

Though in the Government service for over a quarter of a century, he always chafed under the minor restrictions and regulations imposed by law. A strict constructionist in all important matters, it was sometimes hard for him to bring himself to acknowledge authority in minor matters. It was long one of the jokes in the office that the Chief Geologist was the only member of the Survey who refused to obey certain minor regulations. This attitude of mind made him very lenient with the transgressions of others who might overlook some regulations which the Government service of necessity imposes.

Hayes was essentially the child of his puritanical ancestors and had what is sometimes called the New England conscience. This manifested itself chiefly in his universal fair dealing with men. He had, however, no patience with cant and hypocrisy, and his puritanical ideals did not prevent the development of catholic tastes and tolerance of the opinions of others. By descent of colonial ancestry, brought up in a typical American community, and educated in our own schools, Hayes was in every respect American. The generations of geologists that preceded him were by education or tradition strongly influenced by European thought. Not so with Hayes. He did not cross the Atlantic until the later years of his life, when sent for as an adviser in a great industrial problem. His scientific work was founded on principles largely developed on this continent.

Few men contributed more to the bringing about of the conservation of the mineral resources of the United States than did Hayes. With his usual diffidence, he took no public part in the movement. Nevertheless, in the application of the principle that the mineral resources should be put to their best use both for this and for future generations he rendered very important service. Hayes had small patience with the extremists of either side when the matter became a national issue, but analyzed the problem on a scientific basis. Chamberlain once said of Hayes that one of his most important contributions to the cause was the "conservation of common sense." Hayes's own special task was the supervision of a report on the mineral reserves of the United States, which was demanded as the basis of wise legislation and administration. To this he contributed a chapter on the iron ore resources. It was during his administration of the geologic branch that the important work of classifying the public lands was undertaken by the National Survey. In this field his genius for organization and wise counsel were of the greatest value.

Some have held that Hayes as Chief Geologist led the National Survey from pure to applied science. That the modern trend of geologic research has been toward the making of the science more useful can not be denied; but it is equally true that this is only a part of a world-wide movement demanding that science be applied to the betterment of the conditions of life. Hayes was not responsible for this trend, though in full sympathy with it. He believed the people had a right to expect that the geologist, especially he who was supported by the public purse, should give help in solving the problems of every-day life. He knew full well, however, that the problems of applied geology can only be solved by investigating those giving no promise of yielding immediate economic return. The published record of his stewardship of the geology of the National Survey clearly shows that the needs of pure science were not neglected. The work in applied geology directed and done by him was in no sense a commercialization of the science, but rather placing it on the broad basis of scientific research. Hayes had no patience with short-cuts in geology. Economic work that could not stand the acid test of science he rejected without question.

As shown above, his training and inherent traits gave him a certain lack of sympathy with speculations which were not very closely tied to the facts. He appeared more interested in acquiring the detailed facts than in establishing the broader relations between those facts. This was not true of his physiographic studies, where he showed that he had that quality of scientific imagination generally regarded as essential to the solving of the larger problems of the science. In stratigraphic and structural geology, however, he believed that the larger problems could only be solved by detailed surveys, in the work of which he himself showed a master hand. If a criticism is to be made of his administration, it is perhaps that he sometimes failed to search for the facts dealing with the interpretation of some of the broader and more fundamental problems of the science. He would no doubt reply to such a criticism that until there were more detailed facts the investigation of the larger problems would simply lead into the realm of pure speculation. It is true, moreover, that the broader field of research was by no means entirely neglected, though it was given a less conspicuous place than the detailed studies.

When Hayes joined the Federal Survey only about thirty geologists were on its permanent staff. When he resigned the position of Chief Geologist, nearly a quarter of a century later, the number of geologists had grown to over 100. This growth can be taken as a measure of the public interest in geologic work, and in the last analysis its recognition of the value of the science. The history of geology shows a gradual evolution from the field of pure speculation toward the ultimate goal of exact science, and this evolution has been specially marked during the span of years that Hayes was engaged as a professional geologist. Many influences and many investigators have contributed to this evolution. Hayes must, however, be credited with notable part in advancing this movement. Probably his most notable service rendered the science to which he devoted his life was in the influence he had both as an investigator and as a leader in guiding geologic research toward greater refinement.

Mexican Oil Fields

In 1911 Hayes resigned the position of Chief Geologist to become vice-president and general manager of the Aguila Oil Company of Mexico. Though engrossed in his work and greatly regretting to leave his circle of friends in Washington, yet the inducements offered were such that he could not afford to refuse the new position. While he left the Government service with deep regret, yet he was also greatly interested in both the scientific and administrative problems opened up to him by this change. He was thoroughly familiar with the general situation at Tampico, where his new duties called him. In 1909, in company with Dr. David T. Day, he visited Tampico, and on his return submitted a brief statement dealing principally with the relation of Mexican oil fields to the market for American oils. Later, while on furlough from the Federal Survey, he made private geologic surveys in the Tampico field, and here his methods were to find their supreme test. After detailed stratigraphic and structural surveys he recommended certain drilling for oil. The result showed that his predictions as to the depth of the pool were not only correct within a few feet, but they led to the developing of the famous

"Potrero des Llasso Well Number 4," probably the greatest oil producer in the history of the industry.

One of Hayes's first tasks in his new position was to organize a corps of young American geologists and to set them the task of finding oil pools. This problem had previously been investigated by a number of English and American oil experts and geologists. These investigations had not, as it appears, yielded very practical results; for, as Hayes expressed it,

> "What the company needs is more common sense and less geology,"

a statement he explained by adding:

> "Careful distinction must be made between actual facts and untried theories."

Though Hayes recognized the discovery of oil as his first duty, he also well knew that this could only be accomplished by detailed geologic surveys. Therefore he formulated a broad plan for these investigations that, had it been completed, would have yielded very complete knowledge of the stratigraphy and structure of the Mexican Coastal Plain.

Besides the geologic survey the drilling operations commanded his attention. He imported American drillers, and his bent for mechanics led him to supervise and direct much of the work in person. One of his assistants writes:

> "Doctor Hayes endeared himself to the drillers by his happy faculty in dealing with them. He would visit the rigs, pat the drillers on the back when necessary, talk to them about geology in terms they could understand, tell stories, and in general act in a very human manner."

While giving attention to these details he was also handling many difficult administrative problems. He reorganized the force of technical men, supplanting the inefficient and promoting the efficient. Under his management the company for the first time made a very marked financial success. Lord Cowdry, the head of the company, writes of him:

> "As vice-president of the Mexican Eagle Oil Company and general manager of the exploration and exploitation department, he contributed in a large degree to the marked progress achieved by the company during his tenure of office."

His technical leadership among the many oil producers of the Tampico field was recognized by his being elected to the presidency of the Mexican Oil Association for two successive years.

The first two years of his Tampico residence were among the happiest of his life. His family, except for some of the older children, were with him, and he was associated with a number of men to whom he was strongly attached. His administration was proving a great success and his geologic studies were by no means entirely set aside. He still personally directed the geologic surveys, and often stole away from the office drudgery to visit the geologic and drilling field parties. Then came the cloud of the Mexican revolution, which became deeper as time went on, and had it not been for his personal efforts this would have wrecked the enterprise in his charge. In February, 1913, he writes:

> "You are undoubtedly far better informed than are we as to what is going on in Mexico. At present we are entirely cut off from mail and practically from telegraphic communication. It does not seem possible for existing conditions to continue indefinitely, and they could not be much worse, so they must improve. In Tampico everything is quiet, and we apprehend no serious trouble so long as a warship is anchored outside. The men in the camps are, however, getting very uneasy, and I doubt if they can be held at their tasks much longer. . . . We are employing about 3,000 native laborers in this district, and we are afraid to stop the work, since each one is a potential revolutionist, and he can be kept from revolting only by a good job. In the meantime money is getting short, for we can't draw on Mexico City. . . . I haven't heard a word from there in ten days, and as our office is directly in line of fire between the federal and rebel positions, I fear it is in bad fix. . . . Aside from the political troubles, everything is going well. We have brought our oil shipments up to nearly a million barrels a month and expect to soon increase that."

Ten months later he writes again:

> "The oil fields seem to have occupied the center of the stage for the past month, and I can imagine the kind of news your papers have been serving up. It has been bad enough, but not as serious as reported. We have managed to keep things running most of the time, though having a thousand rebels in our camps for nearly a month did not add much to the efficiency of the various operations. . . . I have put the big well in such shape as to defy the whole rebel army. The controlling valves are covered with a concrete structure six feet or more thick. . . . The three days' fighting around Tampico were somewhat exciting. From the top of our office building the whole battlefield could be seen. We saw the charges and the counter-charges very clearly. I rode over the field Sunday and counted nearly a hundred bodies still unburied. . . . About 350 foreigners took refuge in our office building when the town was attacked. . . . We had the building barricaded with sand bags, armed guards posted, and all preparations made to stand off the mob and the rebels."

Under the modest "we" Hayes veils the fact that he was the commanding personality in the whole situation. As an American at the head of an English company, the largest in the district, operating in a country torn by revolution, his was a position requiring the greatest tact and strained to the utmost his executive ability. In spite of the turmoil, operations never ceased, and for months oil produced from wells in a district in the hands of the rebels was transported by pipe line through the battle grounds and shipped from a port in the control of the federals. This experience brought the final proof of Hayes's tremendous force of character and marvelous executive ability. The most trying experience of his whole career was when, in the protection of the lives of the employees, he felt it imperative to haul down the American flag from the office building where it had long waved with the Union Jack.

Of the causes that forced him and nearly all other Americans to leave Tampico, this is not the time nor place to speak. Suffice it to state, that he was one of the chief instruments in getting the Americans safely out of Tampico during the night after the taking of Vera Cruz, the town being then in the hands of the Mexican mob. When all were gone, his duty done, not only as the head of a great corporation, but also as the brave, patriotic American citizen that he was, he left Tampico never to return.

Personal Reminiscences

Certain important events of Hayes's life not referred to above should here be recorded. On March 22, 1894, he married, at Washington, Rosa Paige, daughter of Nathaniel and Rosa Paige. His widow, three daughters, and five sons survive him. Many honors came to him during his professional career. He was elected to this Society in 1889; was a member of the American Institute of Mining Engineers, and one of the founders of the Mining and Metallurgical Society of America. He received the Walker Prize of the Boston Society of Natural History in 1897. Oberlin College conferred the degree of Doctor of Laws on him in 1908.

While at Tampico Hayes suffered more or less from ill health, and during the height of the political troubles underwent a serious operation. His health returned, to a certain extent, after leaving Mexico and he spent part of a winter in London. Here plans made for explorations for oil in different parts of the world were interrupted by the European war. He returned to Washington with his family and established once more intimate relations with his circle of friends. Soon his health began to fail, and it finally became only too evident that he was suffering with cancer. During the many months of his last illness, though at times suffering terribly, he never lost his courage. As he slowly wasted away, those who watched at his bedside could but marvel that the disease never mastered him. He was fond of discussing geology and, as far as his condition permitted, kept pace with geologic literature. His clearness of mind was maintained up to a few days before his death, and his hope of ultimate recovery lasted almost as long. He died on February 8, 1916.

The great value of Hayes's personal contribution to geology is shown by the published record. It is more difficult to gauge the service he rendered by the guidance and counsel he gave to others. The decade of Hayes's administration of geologic researches in the National Survey was prolific of important results. Though he would be the last to claim credit for the work of others, yet his was the hand which guided it all. There are many geologists of the present generation who owe their first inspiration, their first opportunity for research, to Willard Hayes.

In spite of his great personal achievements in geology, probably his greatest service to the science which occupied his full energies for over a quarter of a century is the assistance he gave to younger investigators. Those who turned to him, whether for help in science or in the personal affairs of life, never found him unsympathetic. No young assistant, no clerk, ever came to him for counsel but he received full measure from a man who was always overwhelmed with important administrative duties. This illustrated the keynote of his character, which was a strong human sympathy, though it was often masked by a reserve of the New England Puritan type. With men of his own generation or older, Hayes was often diffident about venturing an opinion unless circumstances positively demanded it; but if so, he expressed it with clearness and decision.

Willard Hayes was a keen observer and a constructive thinker. Be it in scientific or administrative work, he was ever ready to solve a new problem. But, above all, he was beloved by the men who knew him best. He inspired their confidence, enthusiasm, and admiration. If it is desirable to sum up his character in a single phrase, he should be called *a leader of men.*

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Growth of concretions of different composition under a variety of conditions. Abstract: Science, new series, volume 33, 1911, page 550.

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ANNOUNCEMENT AS TO METHOD OF CONDUCTING THE MEETING

Announcement was then made by the Secretary of the plan of managing and presenting the various papers and exhibits of the program, calling attention to the accommodations that had been made by the local committee for the use of four places of meeting, including the large auditorium for public lectures, a smaller class-room for the general sessions of the Society, another room for the special sessions of the Paleontological Section, and a suite of rooms for exhibits and discussions. It was announced that the plan of presenting the formal papers in long sessions, with definite allowance of time for each paper, would be followed, and that discussions, if of an extended nature, and exhibits of special interest to small groups would be accommodated in the exhibit rooms.

RESOLUTIONS CONCERNING NATIONAL RESEARCH COUNCIL

President Clarke presented certain questions raised by the National Research Council and which had been considered by the Council at their meeting on the previous evening. The following resolution was offered as recommended by the Council of the Society:

Whereas the National Academy of Sciences at the request of President Wilson has taken the initiative in bringing into cooperation existing governmental, educational, industrial, and other research organizations and has brought about the establishment of a National Research Council which shall be representative of these various organizations, and whose object shall be the promotion of scientific research with especial reference to national welfare; and

Whereas we believe that human progress depends in part on the increase in the knowledge and application of the principles and factors of geology, and that national welfare can most effectively be advanced by the cooperation of this Society with coordinated bodies of scientific investigators;

Be it resolved, That the Geological Society of America approve of the establishment of a National Research Council and agree to cooperate in all practicable ways in its work of coordinating and promoting scientific research.

This resolution was adopted by the Society.

The following motion was also presented as coming from the Council:

Moved, That in view of the overture made to this Society by the National Research Council and of the desire of the Geological Society of America to cooperate with the purposes of the National Research Council in securing the most effective application of scientific endeavor in all departments of knowledge, the Council of this Society be authorized to proceed with the formation of a Committee on Geology, after conference with the representatives of the Committees of the National Research Council and the American Association for the Advancement of Science.

This motion was adopted by the Society, and the action of the Council in taking steps toward the formation of a committee in accord with these resolutions was approved.

The Society then proceeded at 11.10 o'clock to the consideration of scientific papers.

TITLES AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE MORNING SESSION AND DISCUSSIONS THEREON

GEOMETRIC PLANS OF THE EARTH, WITH SPECIAL REFERENCE TO THE PLANETESIMAL HYPOTHESIS

BY HARRY FIELDING REID

(*Abstract*)

De Beaumont's Pentagonal System, Green's Tetrahedral System, and Chamberlin's Planetesimal Hypothesis were considered. The last was given special attention. The astronomical part of the hypothesis was not considered, but the supposed division of the earth into six segments, the interaction of these segments and their relation to the great lines of the earth, the origin and permanence of the continents and oceans, etcetera, were discussed.

Presented in abstract extemporaneously.

INVESTIGATIONS INTO THE MAGNITUDE OF THE FORCES WHICH ARE REQUIRED TO INDUCE MOVEMENTS IN VARIOUS ROCKS UNDER THE CONDITIONS WHICH OBTAIN IN THE DEEPER PARTS OF THE EARTH'S CRUST

BY FRANK D. ADAMS AND J. AUSTIN BANCROFT

(*Abstract*)

This somewhat extended investigation has been carried out with a view to obtaining at least an approximate measure of the forces required to induce rock flow under the conditions of differential pressure which obtain at two separate horizons within the earth's crust, and also to ascertain the influence of increasing load on such rock movement in the deeper portions of the crust.

The following rocks were employed: alabaster, Castellino, Italy; marble, Carrara, Italy; black Belgian marble; dolomite, Maryland; steatite, Virginia; slate, New Rockland, Quebec; sandstone, Cleveland, Ohio; granite, Baveno, Italy; diabase, Sudbury, Ontario.

In each experiment a standard cylindrical column of rock was inclosed in a tube of nickel steel of standard dimensions and deformed with a very slow, creeping movement, the pressure being exerted through pistons inserted in the ends of the tubes. Two sets of steel tubes having different wall thicknesses were employed, representing different resistances—that is, different loads of overlying rock, equivalent to different depths beneath the earth's surface.

In this way the "work done" in effecting a certain definite amount of deformation was determined in the case of each rock and the relative ease with which the different rocks were deformed was given mathematical expression.

The results obtained from this investigation throw light on a number of problems presented by the zone of flow. They show that certain of these problems which have been made the basis of mathematical analysis must be reconsidered, and they provide data for this reconsideration. Among other results, it is shown that in going downward in the earth's crust there is a rapid increase in the rigidity of rock masses, so that a continuously greater force is required to effect their deformation. Movements, therefore, take place much more readily in the upper portion of the zone of flow than in its deeper parts. This fact has an important bearing on the questions of isostasy and orogenic movements.

Presented in abstract extemporaneously by the senior author.

DISCUSSION

Prof. GEORGE H. CHADWICK asked whether the postglacial uplift of the Great Lakes area and Canada involved a deep-seated or a comparatively superficial transfer of matter underground.

Mr. E. W. SHAW: Professor Adams has attempted to reproduce conditions existing within the earth, but apparently his test specimens were dry and at ordinary temperature. What effect would the presence of water and higher temperature have on the results?

Professor ADAMS' reply to Mr. Shaw: As stated in the paper, this investigation deals only with the effects produced by pressure. Our previous work has shown that heat tends to increase the ease with which movement takes place.

Prof. R. T. CHAMBERLIN: I have listened to this paper with very great interest. It seems to me that the fundamental importance of these experimental researches and the resulting view that the rigidity of the rocks increases with increasing depth below the surface can scarcely be overestimated, for they are providing firm and solid foundations for the whole subject of earth deformation. But there remains to be overcome one troublesome factor on which some of us would welcome additional light. That is the evaluation of the time element. I should like to ask Dr. Adams whether very much lesser stresses acting through a much longer period of time, as would be the case in the earth, might not produce the same results as the greater stresses acting through a short period of time. Or has it been found possible in any way to compensate for the short length of time included in the experiments and thus minimize this troublesome factor?

Professor ADAMS' reply to Professor Chamberlin: In order to eliminate the time factor as far as possible, the experiments were arranged so that the rocks were deformed with a very slow, uniform, creeping movement. The time factor is discussed in the paper, but I am unable to state just how far it would influence the result.

Remarks were made also by Messrs. H. F. Reid and Charles Schuchert, with reply by the author.

METAMORPHISM AND ITS PHASES

BY REGINALD A. DALY

(*Abstract*)

An historical review of the word "metamorphism" discloses at least six extant definitions. All are quite different in principle and yet all have been actively used since 1900. A similar lack of unanimity is seen in the use of "regional metamorphism," "dynamic metamorphism," "static metamorphism," "contact metamorphism," "pressure metamorphism," "thermal metamorphism," and most other names of the phases. The great need of a common vocabulary relating to this subject has prompted the effort to frame definitions of the more important terms. In the nature of the case, that program runs parallel with the equally difficult task of constructing a rigorous classification of metamorphic processes.

A proposed classification follows:

A. Regional metamorphism (not caused by eruptive bodies).
    I. Static metamorphism (orogenic movement not a causal condition).
        1. Stato-hydral metamorphism or hydro-metamorphism (low temperature).
        2. Stato-thermal metamorphism or load metamorphism (high temperature).
    II. Dynamic metamorphism (orogenic movement a causal condition).
        1. Dynamo-hydral metamorphism or slaty (?) metamorphism (low temperature).
        2. Dynamo-thermal metamorphism or friction (?) metamorphism (high temperature).

III. Dynamo-static metamorphism (load metamorphism in rocks lying beneath overthrust blocks).

B. Local metamorphism (caused by eruptive bodies).

I. Contact metamorphism (magmatic influence in control).

II. Load-contact metamorphism (combination of magmatic influences, the earth's body heat, and dead weight stress).

This table and the corresponding definitions are offered for discussion and improvement.

Presented in abstract extemporaneously.

Brief remarks were made by Prof. C. K. Leith.

STUDY OF THE RECENT ACTIVITY OF MAUNA LOA

BY ARTHUR L. DAY

(*Abstract*)

The conditions surrounding the violent summit eruption of December and January, 1914 and 1915, and the accompanying lava flow within the summit crater were described, together with some discussion of the dynamic relations involved. At this summit eruption the volume of gas was enormous, the temperature very high, and the lava of unusual texture. Following this, an outbreak of gas took place in May, 1916, on the mountain side near the 10,000-foot level. The explosions were of great violence, but little or no lava was ejected. Toward the close of the month an outpouring of lava took place on the same side of the mountain, but at the 7,000-foot level, in which two streams emerged from the radial rift zone, each flowing about 8 miles. This eruption was characterized by wholly different physical features, with much lava, little gas, and low temperature.

Presented in abstract extemporaneously.

At 12.15 o'clock the reading of the regular scientific papers was discontinued, and a public address was given in Chancellor's Hall on "Geology and Public Service," by Hon. George Otis Smith, Director of the United States Geological Survey.

At the conclusion of this address the Society was adjourned, to reconvene at 2 o'clock.

The Society was called to order at 2 o'clock, with President Clarke presiding and Doctor Berkey acting as secretary, and took up first the matter of the Branner geological map of Brazil, presented by the Council. It was explained in behalf of the Council that a complete geological map of Brazil has been prepared by Doctor Branner and is offered to the Society for publication. The issuing of such a map involves much greater expense than is usual for a contribution in regular series, and the Council recommended the approval of an appropriation for this purpose. Remarks were made by different members of the Society, favorable to the undertaking, and action was taken supporting the Council in setting aside funds sufficient to issue this map with suitable accompanying descriptive matter. The committee appointed to superintend this special work consists of J. C. Branner, Bailey Willis, and W. B. Clark.

TITLES AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE AFTERNOON SESSION AND DISCUSSIONS THEREON

AGES OF THE APPALACHIAN PENEPLAINS

BY EUGENE WESLEY SHAW

(*Abstract*)

A review of the literature discussing the ages of the widely known peneplains of the Appalachian province brings out the fact that notions concerning their age are discordant, and an examination of published and unpublished data leads to the inference that the peneplains are as young or younger than the latest date so far assigned: For example, the so-called Cretaceous peneplain is assigned by various writers to pre-Cretaceous, Lower Cretaceous, Upper Cretaceous, and early Tertiary time. The best basis for dating surfaces regarded as remnants of this peneplain seems to be obtained (1) by correlating them with unconformities or deposits in the coastal plain, and (2) by determining their extent and the amount of erosion to which they have been subjected. The result seems to suggest that such surfaces are not much older than Middle Tertiary, and that other Appalachian peneplains are still younger.

Read in abstract from manuscript.

DISCUSSION

Prof. FRANK LEVERETT stated that he has noted the preservation of oyster beds of Niobrara formation on the crest of the Mesabi iron range near Cloeraine, Minnesota, that appear to be the latest marine deposit of that region. The deposits are evidently *in situ* with an associated soft, shaly material resting on the iron formation. If, as suggested by Mr. Shaw, erosion has broken down the Appalachian region hundreds of feet below the level of any exposed surface of Cretaceous age, it becomes important to account for preservation of these beds in Minnesota. They do not seem to have had any superincumbent beds removed. They are apparently beds formed near an old coastline.

Author's reply to Professor Leverett: I had no intention of contending that no area outside the Appalachian province had been exposed since Cretaceous time without suffering reduction, though my belief is that such areas are rare and small. I should think that the Mesabi Range Cretaceous, even though a coast or stream deposit, might have been deeply buried under later Cretaceous or Tertiary deposits for a considerable part of their history.

Further remarks were made by Prof. R. A. Daly.

COMPARISON OF THE EUROPEAN AND AMERICAN SILURIC

BY AMADEUS W. GRABAU

(Abstract)

During the summer and fall of 1910 much time was spent in the study of the Siluric formations of England, Scotland, Sweden, Bohemia, and the island of Gotland, and extensive collections made. Clear evidence has been obtained in the field as well as from the study of the faunas that only two great divisions of the Siluric are represented in Europe as in America. These are the Lower and the Upper Gotlandian, corresponding to the American Niagaran and Monroan. The Middle Siluric or Salinian of America is unrepresented in Europe, except possibly in the extreme west, there being throughout a marked hiatus and disconformity between the Lower and the Upper Siluric. The disconformity is frequently well marked physically. The Lower Siluric comprises the Lower Gotlandian of Sweden, the Llandovery, Wenlock, and Lower Ludlow of western England, Etages 6, 7, and 8 (Lower and Upper Llandovery and Lower Wenlock) of Norway, Etages Ee_1 and Ee_2 of Bohemia, and corresponding deposits elsewhere in Europe. The Upper Siluric is best represented in the Baltic region, where it comprises the Upper Gotlandian, while in the Christiania region it is represented by Etage E9 (Upper Ludlow) and by the Upper Ludlow and succeeding continental beds of England and Wales. In Bohemia Etage Ff_1 represents this horizon, which has much in common paleontologically with the Upper Monroan of North America. In the Baltic region the sediments are mainly calcareous and the fauna of the Siberian type. In Great Britain the sediments are to a considerable extent of deltaic and near shore, often partly terrestrial, type, with an Atlantic fauna in parts, of which graptolites, stranded on the mud flat surfaces, predominate. The Siberian fauna advanced westward in Wenlock time, partly replacing the Atlantic fauna. It apparently entered North America by the northern route, while the Atlantic fauna entered by way of the Saint Lawrence channel. At the end of Lower Siluric time the sea retreated from most of Europe and erosion followed. In Upper Siluric time the sea readvanced from Siberia and from the Atlantic with a progressive overlap of the various formations. Though many species characteristic of Lower Siluric (Niagaran) have persisted in the two centers of distribution and returned with the return of the seas, there were also many new types which entered the regions for the first time. The spread of the continental type of sedimentation in Upper Siluric time also caused a change in faunas, introducing the river element to a considerable extent.

Presented in abstract extemporaneously.

DISCUSSION

MR. M. Y. WILLIAMS: In the central part of the Niagara Peninsula of Ontario, north of the town of Dunnville, the records of four gas wells indicate an erosion channel in the top of the Niagara-Guelph formations. The thickness of these formations is shown to vary from 200 to 250 feet, a channel 50 feet deep and four miles or more across, with an easterly direction, being the natural explanation of the phenomena.

Prof. W. H. TWENHOFEL: Worn shells and gravels occur throughout the Gotland section and have very little significance in so far as the existence of a stratigraphic break is concerned. Many, if not all, of the phenomena described in the paper are to be referred to the influence of the coral reefs. The strata and faunas on opposite sides of the reefs are different. Discordances of strata are common and mean nothing in terms of a stratigraphic break.

Further remarks were made by Miss O'Connell.

EVIDENCE AS TO THE MODE OF FORMATION OF COAL DERIVED FROM THE DEPOSITS OF JAPAN, CHINA, AND MANCHURIA

BY E. C. JEFFREY AND KONO YASUI

(*Abstract*)

Through the kindness of various geologists in Japan and eastern Asia, we have been able to investigate the organization of the coals of these regions by means of the improved methods devised by one of us.

Coals from the Mesozoic and Tertiary of Japan, from the island of Hokkaido southward, show evidence of being composed of modified vegetative structures intermingled almost invariably with spores often present in such large amounts as to result in a canneloid appearance. For the most part the vegetative remains in the coal have lost their structure except when partially or wholly in the condition of charcoal. The frequently large spore content of Japanese coals, even of those belonging to the category of steam coals (for example, the Takashima or Nagasaki coals), as well as the occasional presence of isolated fragments of charred wood or mother of coal, so called, vouch for their accumulation by open water deposition.

Similar results were obtained from the examination of coals of various geological ages from China and Manchuria. The Oriental coals consequently supply further and convincing evidence for the deposition of the raw material of coal in open water.

Presented in abstract extemporaneously by the senior author.

PETRIFIED COALS AND THEIR BEARING ON THE ORIGIN OF COAL

BY E. C. JEFFREY

(*Abstract*)

In various European coal deposits petrifactions have been found in coal seams, which are commonly called "coal balls." The author has recently devised methods of investigating the coals which are present in coal beds containing coal balls. It appears from examination of somewhat numerous samples from England (Lancashire and Yorkshire), from Germany (Westphalia), and Russia (Donetz coal field) that such coals are not normal coals. Their reaction to chemical reagents is quite distinct and they are free from the quantities of spores which are characteristically present in coals from all parts of the world and every geological age. Their structure is homogeneous except

for the occasional presence of fragments of burned wood or "mother of coal." The organization present in these coals is, in fact, that which might theoretically be expected from the carbonization of ordinary peat. The presence of isolated fragments of charred wood, both in the substance of such coals as well as in the petrifactions occurring in them, indicates clearly that they have been laid down in open water, precisely as is the case with many lignite deposits of the Cretaceous of the coastal plain. In these deposits often occur large quantities of the vegetative remains of plants, isolated fragments of which are in a charred condition. It is universally admitted that the Cretaceous lignites of the seaboard and the coast islands were deposited in open water. The petrifactions in coal accordingly do not furnish valid evidence for the *in situ* mode of deposition of coal, as is often assumed.

Presented in abstract extemporaneously.

ORIGIN OF VEINLETS IN THE LIMESTONE, SHALE, AND GYPSUM BEDS OF CENTRAL NEW YORK

BY STEPHEN TABER

(*Abstract*)

Metalliferous veins commonly furnish little or no evidence relative to the mechanics of their formation, because they usually occur in regions of metamorphic rock and because such evidence as may have existed during the early stages of vein formation has usually been obliterated by alterations due to the vein-forming solutions or to secondary changes. For this reason the small veins found in regions of unaltered sedimentary rocks furnish clearer evidence bearing on this problem.

Many small veins, ranging up to two or three inches in width, are exposed in the limestone and gypsum quarries of Cayuga and Onondaga counties, New York. These veins may be divided into two classes—one fibrous and the other coarsely crystalline and non-fibrous. The former are composed either of gypsum or calcite, the crystal fibers extending transverse to the strike of the veins, which run in all directions, but are generally parallel to the bedding. These veins are lenticular and continue for short distances only. The non-fibrous veins usually consist of gypsum or calcite, but the calcite veins sometimes contain more or less quartz and pyrite. They are more persistent and more uniform in width than the fibrous veins, and most of them are vertical or steeply inclined. Both types frequently contain inclusions of the wall rock.

According to the author's theory, the fibrous veins were formed by a process of lateral secretion, additions of new material reaching the growing vein only through the walls, while the non-fibrous veins were deposited from solutions that diffused between the walls. Both the fibrous and the non-fibrous veins furnish much evidence indicating that they were not deposited in preexisting openings, but that the growing veins have made room for themselves by pushing apart the inclosing walls.

Presented by title in the absence of the author.

BARITE DEPOSITS OF MISSOURI

BY W. A. TARR[1]

(Abstract)

The most important barite deposits of Missouri are those in Washington County, in the southeastern part of the State; but other important deposits occur in the central part of the State. The barite which is mined in Washington County occurs as nodules and fragments, scattered through a deep, red, residual clay. Associated with the barite are considerable chert and drusy quartz and occasionally galena. The barite in the residual clay was derived from veins in the Potosi and Proctor dolomites of Upper Cambrian age. The barite is found only in association with these two formations. The barite is believed to have been deposited by rising hot solutions.

Presented in abstract extemporaneously.

THE MAGMATIC SULFIDS[2]

BY C. F. TOLMAN, JR., AND A. F. ROGERS

(Abstract)

Our study of the magmatic ores has included a review of the field data regarding these deposits and a study by all available microscopic methods of numerous suites of specimens from Sudbury and Alexo, Canada; Engels Mine, Plumas County, and Friday Mine, San Diego County, California; deposits at Litchfield, Connecticut; the Golden Curry Mine, in Montana; certain of the deposits in Norway, Saxony, and Bohemia, and the Ookiep mines, in South Africa.

As a result of these studies, we have concluded that the magnetic sulfid and oxid ore minerals are formed after the original silicates of the rock, and at their expense by replacement. Moreover, both euhedral and anhedral masses of magnetite are later than the silicates. The formation of the ores, however, was not accompanied by destructive pneumatolytic or hydrothermal action, for the solutions or mineralizers which brought in the ores were sufficiently "in equilibrium" with the silicates so that replacement took place without the development of secondary silicates by destructive action.

It is shown definitely that extensive hornblendization of the pyroxenes precedes the formation of the ores, and that chlorite, tremolite, anthophyllite, sericite, and serpentine are distinctly later than the magmatic ores.

We attribute hornblendization and the formation of the ore minerals to a late magmatic stage, and the alteration products mentioned above to a hydro-

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[1] Introduced by E. B. Branson.

[2] A complete statement of the results of this investigation is in press: A study of the magmatic sulfid ores, Leland Stanford Junior University publications, University series (1916). A short summary dealing with the Sudbury ores will appear in the Engineering and Mining Journal, February 3, 1917, under the title: The origin of the Sudbury ores.

thermal stage. There has been only slight migration and secondary transfer of the ore minerals subsequent to the magmatic stage.

The paper emphasizes the rôle of mineralizers in magmatic differentiation.

Presented by title in the absence of the author.

LOCAL GLACIATION IN THE CATSKILL MOUNTAINS

BY JOHN L. RICH

(*Abstract*)

This paper presents certain results of a study of the glacial geology of the Catskill Mountains made during the past summer for the New York State Geological Survey.

Evidence is presented which indicates that in the closing stages of the Glacial period independent local glaciers, some of them several miles long, occupied many of the higher mountain valleys. Certain features suggest the possibility that instead of being entirely lingering remnants of a waning ice-sheet, the local glaciers may have been in part developed independently during an advance of the continental glacier which failed to override more than the northern and eastern borders of the mountains.

Presented in abstract extemporaneously.

DISCUSSION

Dr. **FRANK B. TAYLOR**: I visited the Fly Brook locality in 1908 and found the moraines beautifully formed, and evidently formed by an ice-tongue coming from the mountain range to the south or southwest. It seemed to me, however, that the ice-tongue came from a gap or col in the range rather than from the higher part of the range. The so-called "pedestals" which Mr. Rich describes as occurring in small side ravines seem to me to correspond to certain forms of lateral moraines which are common in the Taconic Range in Massachusetts and southern Vermont. In a number of cases I found eskers and border drainage associated with them in such a way as convinced me that they are lateral forms of the main valley tongue rather than terminal moraines formed by tongues descending the side ravines.

Author's reply to Doctor Taylor: The pedestal moraines do not appear to be lateral moraines. They commonly bulge outward into the trunk valleys and are, in some places, almost fan-shaped, being highest in the center. The theory that they may be lateral was considered in the field and rejected for most, but not all, pedestals.

Prof. **J. W. GOLDTHWAIT**: Mr. Rich's interesting observations in the Catskills appear to conflict in two respects with those made by me in the White Mountains of New Hampshire. (1) In the White Mountains cirque sculpture seems to be confined to the sides of summits that approach or exceed 5,000 feet altitude, and even then to appear only where there was opportunity for the catchment of exceptionally large amounts of drifting snow. The Catskills have an altitude of only about 3,000 feet and lie farther south than the White Mountains. (2) The local glaciation in the White Mountains appears to have been chiefly, if not wholly, before the last advance of the continental ice-sheet, and to have been feeble or absent in the closing stage of the last glacial epoch, judging from the lack of definite local moraines and the limitation of local debris to the heads of the cirques. These seeming contradictions in the reports from the two fields do not necessarily mean, however, that either one of us is at fault. It may be that the Catskills, uncovered early in the glacial retreat, received local snowfall and bore local glaciers, while the continental ice-border rested close at hand. It may be, also, that the White Mountains, uncovered later, after the climate had moderated much more, failed to receive the heavy snowfall necessary to support local glaciers.

Author's reply to Professor Goldthwait: The evidence for the *local* origin of the ice which produced such moraines as those of Fly Brook seems to me unquestionable. They lie in valleys opening northward and northeastward and are distinctly convex down valley in a direction directly opposed to that of the motion of the continental glacier. It is true that at Fly Brook there is a col at the head of the valley, but this col opens southwestward; and any glacier which spilled through it northeastward must itself have been of the local or plateau-local type.

Mr. Martin asked whether it had been possible to study the rock materials in the local moraines to see whether they support the view presented.

Author's reply to Mr. Martin: The materials of the moraines were examined. They are almost exclusively local Catskill shales and sandstones. The value of the nature of the material as a criterion is not great, however, because of the large area of nearly uniform rocks in the mountains and the fact that, except opposite the northern and eastern passes leading into these mountains, there are surprisingly few foreign erratics anywhere to be found.

In reply to question raised by Professor Grabau, Professor RICH said: It is impossible to determine with certainty from the content of the till whether moraines in the Catskills are to be ascribed to local glaciers or not. The continental glacier certainly overrode the mountains at its maximum flood and may have left erratics which later would be incorporated with the moraines of truly local glaciers.

EVIDENCES FOR AND AGAINST THE FORMER EXISTENCE OF LOCAL GLACIERS IN THE GREEN MOUNTAINS OF VERMONT

BY JAMES WALTER GOLDTHWAIT

(*Abstract*)

The question of the former existence or non-existence of local glaciers in the Green Mountains has met the attention of several observers, and since the time of Edward Hitchcock has invariably been answered in the affirmative. The evidences adduced to prove local glaciation, mainly by Edward Hitchcock and his son, Prof. Charles H. Hitchcock, are varied, but include in particular: (*a*) Striation accordant with valleys, but not in all cases accordant with those of the continental glacier, and (*b*) "terminal and lateral moraines" and "moraine terraces" in valleys issuing from the Green Mountains.

Inquiry into these evidences shows that it is possible to ascribe all to the work of the continental ice-sheet and associated drainage during the state of

glacial retreat. A study of the topography and surface geology of the country at the alleged heads of the "local glaciers," including the slopes of Mount Mansfield and Camels Hump, where, if anywhere, local glaciers might be expected to have left their records, brings to light not only an entire absence of cirques and trough valleys, but the presence in their place of graded mountain sides and typical torrent-worn valleys, and also of deposits of temporary lakes which must have been held in by the continental ice-sheet as it retired toward the north.

The conclusion is drawn that local snowfields and glaciers did not exist in the Green Mountains at the close of the last Glacial epoch.

Presented in abstract from notes.

DISCUSSION

Prof. **G. FREDERICK WRIGHT**: In the ablation of a glacial ice-sheet the mountain tops will first appear as nunataks. Whether they will support independent glaciers will depend on their height, the amount of snowfall, but chiefly on the extent of surface to retain the snow. The Green Mountains form a much narrower range than the Catskills and have only isolated peaks reaching the same heights; hence were not so likely to support glaciers. It is evident that the Champlain Valley, between the Green Mountains and the Adirondacks, remained full of glacial ice long after the mountain tops on either side were exposed, and that, as the ice diminished, there were extensive terraces formed on the mountain sides at different levels by streams held at those levels by the ice on one side. In many cases these might be mistaken for moraines.

Prof. **GEORGE D. HUBBARD** raised the question if Doctor Goldthwait was familiar with the eastern side of the Green Mountain Range as shown on the Wilmington sheet, United States Geological Survey Topographic Atlas. Professor Hubbard presented a statement of strong development of moraines, eskers, and kames in the valleys and around the mouths of mountain valleys, at the head of some of which are cirques—in one cirque three moraine loops and behind each of two a lake. Moraines seem to be definitely related to the valleys heading up on the mountain slopes and have not been in the least disturbed by any later glaciation. The ice could not have spilled over the mountains and come down these valleys. It might possibly have come through a high notch from the Wardsboro Valley north; but that source could not have supplied ice-tongues to build moraines so closely related to the valleys heading on the eastern face of mountains to the west. A map of the moraines and associated features was shown.

Prof. **JOHN L. RICH**: It has impressed me that the speaker is expecting to find evidences of more marked erosion and cirque-sculpturing by local glaciers than they are likely, in most places, to have produced. If the local glaciers were lingering remnants of the continental ice-sheet, it seems likely that many of them may have occupied the valleys too short a time to have produced the marked erosional effects—truncated spurs and strongly cut cirques—mentioned by the speaker.

DATE OF LOCAL GLACIATION IN THE WHITE MOUNTAINS, ADIRONDACKS, AND CATSKILLS

BY DOUGLAS W. JOHNSON

(*Abstract*)

Professor Goldthwait has presented evidence indicating that the cirques and other topographic features of the White Mountains, due to local glaciation, were formed before the advance of the great ice-sheet and not after its retreat. Certain details of White Mountain physiography are capable of simple explanation on the basis of this suggestive hypothesis. It is believed, however, that they may also be explained without postulating so early a date for the local glaciation, whereas other elements of the topography seem to require appreciable activity of local glaciers after the continental ice had disappeared from the White, Adirondack, and Catskill Mountains.

Presented in abstract extemporaneously.

Discussion

Prof. J. W. Goldthwait: Until now I had supposed that local moraines should be expected wherever strongly developed cirques gave evidence of recent vigorous glaciation of valleys; but if cirques in the Carpathians and elsewhere are unaccompanied by local moraines, and there is no possibility there of subsequent regional glaciation, then of course lack of local moraines should not have been used in the White Mountains as a criterion to fix the date of the local cirque-cutting glaciers around Mount Washington. A piece of evidence which is pertinent to this question of the date of local glaciers in the White Mountains appears in three lantern slides which I ask leave to show. These photographs, taken near the upper part of the headwall of the Ravine of the Castles, a cirque on Mount Jefferson, show ledges which have the form of "rôches moutonnées," made by the continental ice-sheet as it pushed southeastward against the headwall and ascended it. Although the ledges fail to show grooves, being made of mica schist roughened by exposure to the weather, their form is as characteristic as that of ledges which, in any other situation in the glaciated area, would be accepted without question as evidence of the passage of the ice-sheet; and the trend of the "rôches moutonnées" is parallel to striæ on neighboring veins of quartz.

At this point the scientific papers were discontinued for the purpose of attending a public address given in Chancellor's Hall on "The Pulse of Life," by Prof. Richard S. Lull, of Yale University.

At the conclusion of the address the session was adjourned for the day, to reconvene on the following morning at 9 o'clock.

ANNUAL DINNER

The annual dinner of the Society was held at the Ten Eyck Hotel on Wednesday evening, about 175 persons participating. Prof. B. K. Emerson was guest of honor and toastmaster, and the speakers of the evening were Messrs. John M. Clarke, Emmanuel de Martonne, John H. Finley, Frank D. Adams, and William North Rice.

Session of Thursday, December 28

The Society reconvened at 9 o'clock on Thursday morning, December 28, President Clarke presiding, and took up certain matters of business preceding the consideration of scientific papers.

REPORT OF THE AUDITING COMMITTEE

Doctor White read the following report of the Auditing Committee:

> We, the Auditing Committee, have checked the Treasurer's report for the year ending November 30, 1916, and find the same correct so far as items relating to receipts and expenditures. The list of securities will be checked later by a member of the committee (Mr. Brooks) with the securities in Baltimore. The interest payment of $50 credited to the Saint Louis, Iron Mountain and Southern Railroad bond should apparently have been credited to the Saint Louis and San Francisco Railroad Company bond.
>
> I. C. White, *Chairman.*
> Alfred H. Brooks.
> Henry B. Kümmel.

The report was accepted.

The printed report of the Council, including the report of the Treasurer and other officers, was then taken from the table, on motion, and accepted.

GEOLOGICAL EDUCATION FOR ENGINEERS

President Clarke presented the matter of geological education for engineers, calling attention to the fact that about 140 institutions in the United States give engineering degrees. In the course of an investigation of the amount of geology given in the form of regular instruction in these institutions it was found that out of an average of 4,000 hours of work approximately 40 hours are given to geology. It was pointed out that in view of the considerable importance of geology in connection with large engineering enterprises, and in view of the large number of cases of more or less complete failure because of a lack of thorough understanding of geological conditions, it should be considered a very suitable field of activity for the Geological Society to urge a better preparation in the schools of engineering. This might be considered an educational undertaking for the Geological Society of America, and some formal action by a body of this kind would probably have greater weight, both with the institutions of learning and with engineering societies and organizations, than would individuals or small groups. Remarks were made by Messrs. Tyrrell, Atwood, Lane, Hotchkiss, C. W. Brown, Berkey, Woodworth, Shaw, and Matthew. A motion was made by Messrs. Lane and Atwood that a Standing Committee on Engineering Education be named by the Chair, the President to be one member, and that the work of the committee be directed to the encouragement of increased attention to geologic education, to the collecting of information emphasizing the importance of geological advice in engineering work, and to the recommending of other steps calculated to secure the closer working of geologists and engineers.

The Society then took up the consideration of scientific papers.

PAPERS, TITLES, AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE MORNING SESSION AND DISCUSSIONS THEREON

A METHOD OF MEASURING POST-GLACIAL TIME

BY W. O. HOTCHKISS

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LOCALITY SELECTED FOR STUDY

Lake Mendota, at Madison, Wisconsin, is situated about 8 miles from the outermost moraine of the Green Bay lobe of the latest Labrador ice-sheet. Its basin is carved in Upper Cambrian sandstone. Below water level it has fairly steep slopes, down to depths of 60 feet, and a large area, comparatively flat, comprising nearly one-third of the bottom, which lies between the depths of 60 and 80 feet. The bottom deposits are coarse sands in the shallower waters and mud and marl in the deeper portion. These facts are taken from the work of Birge and Juday, published in the reports of the Wisconsin Geological and Natural History Survey.

This marl and mud deposit has accumulated since the retreat of the Green Bay lobe. Obviously, if we could determine the *amount* of deposit and the *rate* at which it was deposited, we would have a very definite measure of the lapse of time since the ice retreated from the basin.

An investigation of these facts is now being planned, and this paper is presented at this time in the hope of receiving helpful suggestions from others who have considered related problems, and also with the hope that others may be interested in undertaking similar studies at the same time, and thus furnish checks on the results from different parts of the country.

THE BOTTOM AND HOW IT REACHED ITS PRESENT CONDITION

When the ice retreated from the lake basin it doubtless left a bottom of sandstone, till, sand, boulders, gravel, and clay. Wave and current action in the deeper portions of the lake have apparently been able to accomplish little or no erosion. Deposition has been the dominant physical process. To what extent small, deep holes may have existed and been filled is unknown. This is one of the facts to be determined. At present it seems probable that in the main part of the area below a depth of 60 feet the bottom is a layer of mud and marl, comparatively uniform in thickness, of which we have but one analysis,[1] as follows:

Loss of H_2O at 105 degrees	1.29
Loss on ignition (organic matter and CO_2)	41.99
SiO_2	15.85
$Fe_2O_3 + Al_2O_3$	2.51
CaO	33.21
MgO	2.16
Na_2O	0.95
K_2O	0.34
SO_3	1.37
Total	99.67

The amount of CO_2 necessary to satisfy the CaO and MgO is 15.77 per cent, which would leave 26.22 per cent as organic matter.

This marl and mud mixture reached its present position by deposition of material carried in by winds and streams, and that brought into suspension by wave action in the more shallow portions of the lake and transported by current; by deposition of carbonates abstracted from the water by the abundant organisms; and is also, in some considerable part, made up of the decaying remains of the various forms of life which have existed in the water. Whether any of the marl has been removed by solution is not known, but evidence for this must, of course, be sought.

DETERMINATION OF AMOUNT OF SEDIMENT DEPOSITED

It is proposed to make determinations in many places; if possible, in some manner by which sections or borings, complete and uniform from top to bottom, can be taken out, dried, and weighed. The various portions will be examined microscopically and chemically. When it is stated that the material varies from a soft ooze at the top to the consistency of a stiff clay at greater depths, it is evident that it is not going to be easy to get satisfactory borings. Any suggestions that will help to accomplish this will be most gratefully received.

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[1] E. A. and Juday C. Birge: Wis. Geol. and Nat. Hist. Survey, Bull. xxii, p. 172.

Determination of Rate of Deposition

It is proposed to place sediment pans in each of the locations where the borings are made and collect the deposit which accumulates. One plan that seems desirable is to make these pans with a permanent partition in the middle, so that collections can be made at short intervals from one-half and the sediment allowed to accumulate in the other half for a full year before it is removed. This will tell whether or not part of the material is taken back into solution at certain times in the year when the water becomes more strongly acid.

From such data as are at hand it appears that the deposit for each year will be sufficient in amount to be measurable with accuracy; in fact, it was surprising to find the amounts so large when the following quantitative estimates were made.

In experiments relating to bottom temperatures, carried on by Birge and Juday, they drove pipes 7 or 8 feet without penetrating through the marl; so that we know there is a greater thickness of marl than this. Marl deposits as thick as 30 feet are not uncommon. Therefore 3 meters and 8 meters may be taken as reasonable limits of the thickness that exists in Lake Mendota. If the duration of post-Glacial time be assumed to be between the limits of 8,000 and 80,000 years, the yearly deposit for the shorter time would be between 960 and 360 grams per square meter. For the 80,000-year period it would be between 96 and 36 grams per square meter. The average thickness of the annual deposit would be one-tenth millimeter if the deposit were 4 meters thick and post-Glacial time assumed at 40,000 years. These are merely estimates to give some idea of the conditions of measurements that must be met.

If annual layers can be distinguished and counted, they will make a very good check on the quantitative measurements. Doctor Birge states that certain minute crustacea (Daphnia) deposit their winter eggs in cases (ephippia) in great abundance, and so offer a possibility that careful study will make possible the identification of annual layers. The careful quantitative study of the plankton now being carried on by Birge and Juday for the State Survey may also suggest other criteria of value.

Factors affecting Accuracy of Results

These may be divided into two classes—the mechanical and the general. Suggestions relating to the points mentioned, or others, will be most gratefully received.

In the first category are included:

1. The difficulty of getting a complete core of a length possibly as great as 8 or 10 meters in depths of water varying from 60 to 80 feet.

2. The difficulty of handling and drying this core to preserve it in good condition for study.

3. The difficulty of getting the deposit in pans. Here must be considered the stirring up of the bottom when the pans are set; the devising of some satisfactory method of marking the location so that inquisitive fishermen and boating parties will not disturb them; the possible influence of the material

the pans are made of on the rate of deposition, and the effect of setting the pans above the level of the bottom.

In the second category are included all factors that may have operated to change the rate of deposition at various periods during post-Glacial time or to remove material once deposited. Some of these are:

1. Possible changes in climate of a large order that in the past may have resulted in a greatly different rate of deposition of either silt or marl.

2. Changes of climate in shorter cycles that may have caused pulsations in the rate of deposition. In such case the danger would be that present-day observations of the rate of deposition might be located in any part of the cycle, and it would be impossible to tell from them what the true average rate has been in the past.

3. Changes in level of the lake may have influenced the rate of deposition. Formerly it was larger than at present. Then it was gradually lowered to a stage 4 or 5 feet below the present level, to which it has been raised by a dam. It is believed, however, that these changes have not seriously affected the rate of deposition of carbonates, but have only affected the rate of silt deposition.

4. Great storms of rare occurrence may also have resulted in much more rapid deposition, either of silt or marl, for short periods.

5. Cultivation has exposed the surrounding area to wind and water erosion, so that recent deposits may contain more silt than those in the past. Here, again, it seems improbable that the rate of deposition of carbonates has been materially changed.

6. It is possible that leaching of carbonates was more rapid shortly after the retreat of the glacier than it is at present, due to the larger quantities then present at the surface of the drift. This may have resulted in more rapid deposition.

7. The last complication suggested is the effect of the large percentage of decaying organic matter included with the deposit. What part this may play is not evident at present, but must be carefully considered in interpreting the results.

DISCUSSION

Mr. LANCASTER D. BURLING: It will be of interest in this connection to record that Mr. E. J. Whittaker, of the Geological Survey of Canada, is engaged in the detailed study of MacKay Lake, in the vicinity of Ottawa, and that one of his problems is the lapse of time since the last retreat of the sea from the Saint Lawrence embayment. Lake Mendota is large and the lapse of time depends on a complicated study of the original marl deposits in that portion beyond the reach of sediment. McKay Lake is small and is surrounded by marl outcrops which contribute a very thin annual layer of white, clastic marl. These layers are separated from each other by a darker layer deposited each spring, during the only period in which the lake receives outside drainage, and the calculation of the lapse of time is here being made by actually counting the number of layers preserved in the lake bottom.

Prof. FRANK LEVERETT called attention to an estimate of the length of post-Wisconsin time, made by Dr. J. T. Scovell from the rate of filling of a lake in northern Indiana, which was published some years ago by the Indiana Geological Survey. It is by combining several such estimates that we will reach a proper understanding of the length of post-Glacial time.

POST-GLACIAL MARINE SUBMERGENCE OF LONG ISLAND

BY HERMAN L. FAIRCHILD

(*Abstract*)

Recent study of the extensive sand-plain along the south side of Long Island has developed new facts relating to its origin. All the features of the plain and its relation to neighboring uplifted territory indicate that it was formed beneath the sea. The amount of the submergence and later uplift is shown by the map published as plate 10 in volume 27 of the Bulletin.

Presented by title in the absence of the author.

It was possible at this point to insert an additional paper by G. Frederick Wright.

EXPLANATION OF THE ELEVATED BEACHES SURROUNDING THE SOUTH END OF LAKE MICHIGAN

BY G. FREDERICK WRIGHT

(*Abstract*)

These beaches are three in number—the Glenwood beach, 60 feet above the present lake level; the Calumet beach, 40 feet, and the Tolleston beach, 20 feet. The most difficult facts to account for are numerous peat deposits underneath the Calumet or second beach. To explain this accumulation of peat in that position, resort has been had to the supposition of a temporary land elevation.

But a simpler explanation follows from considering the variations in amount of water passing through the Chicago outlet, occasioned by the opening of the various channels giving access to Lake Michigan of the vast amount of water stored up in the glacial lakes which occupied the Lake Erie basin. Lake Maumee stood 200 feet above Lake Michigan and was lowered 50 feet when the Ubly outlet was opened. Lake Whittlesey stood 150 feet above Lake Michigan and extended over an area of several thousand square miles. This was lowered 50 feet on the opening of the Saginaw outlet. Lake Warren stood 100 feet above Lake Michigan and covered an area much larger than Lake Whittlesey, and it was lowered to approximately the present level when the retreat of the ice opened the Mackinac channel.

Presented in abstract extemporaneously.

DISCUSSION

DR. FRANK B. TAYLOR: The study of the history of Lake Erie during and after Lake Algonquin shows the same sort of oscillations of the level of Lake Erie as those mentioned by Professor Wright for the south shore of Lake Michigan. In the case of Lake Erie the cause was the division of the outflow of the three upper lakes through Ontario without flowing through Lake Erie. This division occurred twice and produced two low stages of Lake Erie when the level was 12 or 15 feet lower than now.

GLACIAL FORMATIONS IN THE WESTERN UNITED STATES

BY FRANK LEVERETT

(*Abstract*)

In the summer of 1916 the writer made the circuit of the chief areas of glaciation in the western United States to compare the glacial formations there with those of the eastern United States.

The three drifts of the San Juan region in Colorado seem to correlate well with the Wisconsin, Illinoian, and the Kansan. The middle or Durango drift has moraines as well preserved as the Illinoian drift, and a weathering and erosion more nearly in accord with the Illinoian than with the Kansan. The oldest, or Cerro, drift is reduced to patches preserved in places where erosion has been at a minimum. Its scanty preservation may seem to indicate that it is older than the Kansan, but conditions for erosion are so favorable in the Colorado field that it is to be expected that a deposit of Kansan age would be largely removed.

In the Yosemite region in California only the western slope of the Sierra Nevada was examined. There are two sets of moraines widely different in age, the younger of which seems to extend from the Wisconsin time into post-Wisconsin. The older set seems to be no older than the Illinoian, for the moraines have good preservation on slopes which are favorable for rapid erosion. They could hardly be expected to be so well preserved if of Kansan age.

In the Puget Sound region in Washington the Admiralty till appears to be as old as Kansan drift, while the Vashon till seems to be of Wisconsin age. In the Mount Rainier region post-Wisconsin moraines are present, as well as those of Wisconsin age. Those of Wisconsin age have a discoloration and weathering to a depth of several feet, while the post-Wisconsin moraines are nearly free from weather staining to within a few inches of the surface. The reference of the Admiralty till to Kansan rather than to Illinoian age is based on: (1) The condition of the till itself as to weathering and alteration. (2) The amount of erosion it seems to have suffered prior to the last glaciation. (3) The occurrence of partly lignitized, interglacial peat above it.

In northeastern Washington the occurrence of a very old drift, probably Kansan, was established by the discovery of till and striated stones on a high divide southwest of Spokane in the vicinity of Cheney. Boulders had been observed in this region and the possibility of glaciation had been suggested by M. R. Campbell in the Northern Pacific Guide Book.

The writer also visited the Yakima Valley, in southern Washington, where erratic boulders occur whose distribution has been referred by earlier students to floating ice. It seems an open question, however, whether this region, like that near Spokane, may have been glaciated in early Pleistocene time.

In central Oregon observations were made west of Sisters on moraines of Wisconsin age which are found down to within five miles of that village. Outwash material around the village is probably of Wisconsin age, but faint ridges two to three miles west may prove to be worn down moraines of pre-Wisconsin age which are nearly buried under later deposits. Flows of basalt have occurred in the district subsequent to the Wisconsin glaciation, the basalt being over the Wisconsin drift deposits.

In the Yellowstone Park only relatively fresh drift, of Wisconsin or post-Wisconsin age, was noted along the stage route. It is doubtful, however, if the entire park area was glaciated at the Wisconsin stage. The Madison plateau may have escaped this glaciation, but have been reached by an earlier one. Investigations were not carried into that part of the park.

In North Dakota the pre-Wisconsin drift in the vicinity of the Missouri River has well preserved moraines and the drift forms a veneer on rather steep slopes as well as on hilltops and valley bottoms. The preservation of these morainic features and of the deposits on the hillsides seems to indicate an Illinoian or Iowan age rather than Kansan.

Presented in abstract extemporaneously.

Discussion

Prof. G. F. **Wright**: The glacial accumulations near Spokane, so far from the recognized glacial area, are certainly of great significance. A similar isolated accumulation of glacial material has just been reported to me 40 or 50 miles south of generally recognized limits of Kansas drift. All this indicates that the "attenuated border" is much more attenuated than we have been accustomed to suppose. It is, however, well known that this attenuated border occasionally has large areas where glacial material is absent.

Further remarks were made by Prof. W. W. Atwood.

SNOW ARCH IN TUCKERMANS RAVINE ON MOUNT WASHINGTON

BY JAMES WALTER GOLDTHWAIT

(*Abstract*)

The famous snow bank at the head of Tuckermans Ravine, which usually lingers into mid-summer, vanishing late in August, probably comes nearest to being a local glacier of all the snow banks of the eastern United States. Its bulk, its compactness, and its situation in the shadow of the headwall of a cirque have suggested that although it is feeble and not usually perennial this snowdrift is glacier-like in its movement. This idea seemed to be confirmed by an experiment made in 1879 by William H. Pickering, who reported that stones placed in line on the top of the snow bank shifted position at a rapid rate, and drew the conclusion that in early summer the snow mass does move like a valley glacier. If this conclusion is correct, it raises the question whether Tuckerman's Ravine and other cirques on Mount Washington have been carved out by typical valley glaciers, as the author has supposed, or by a process of nivation, augmented by landslides and torrent work, as others have thought.

A repetition of Pickering's experiment, last July, on the snow bank, checked by other observations, seems to prove that this drift has no movement of its own, but that the phenomena attributed to a movement of the whole mass are due, instead, to surface ablation and consequent sliding of objects down the inclined surface of the drift. The snow arch is therefore to be regarded not as a miniature glacier, annually recurring on the site of the old, but as the lifeless ghost of that glacier.

Presented in abstract extemporaneously.

RECORDS OF LAKE AGASSIZ, IN SOUTHEASTERN MANITOBA, AND ADJACENT PARTS OF ONTARIO, CANADA[1]

BY WILLIAM ALFRED JOHNSTON

Recent explorations by the author in southeastern Manitoba and adjacent parts of Ontario have brought forth evidence which confirms Mr. J. B. Tyrrell's view that Lake Agassiz had a rising stage owing to the blocking of the northward drainage by an advance of the Labradorean glacier after the partial withdrawal of the Keewatin glacier. The life history of Lake Agassiz was, however, more complicated than was supposed by Tyrrell or by Mr. Warren Upham, through whose work Lake Agassiz is best known. The evidence shows that the Red River basin has been twice flooded by glacial marginal lakes—an earlier one which was associated with the retreat of the Keewatin ice-sheet and a later one associated with an advance of the ice from the northeast. The early lake was largely drained before the inception of the later lake. The advance of the ice from the northeast, which brought the later lake into existence, was not, as Tyrrell supposed, the first advance of the Labradorean glacier, but a readvance of the ice-sheet at a late time during the Wisconsin stage of glaciation; for, as Mr. Frank Leverett has also shown, a till sheet derived from the northeast underlies a till sheet deposited by the Keewatin glacier.

The evidence on which this modification of the life history of Lake Agassiz is based was in part presented by the author in a paper published in the Journal of Geology, volume XXIV, 1916. Further evidence found in southeastern Manitoba and adjacent parts of Ontario during the past season confirms this view. The evidence consists largely in the fact that a marked depositional break or unconformity occurs at the base of the later Lake Agassiz sediments at various altitudes in the Red River basin. Sections exposed along the Greater Winnipeg Water District Railway between Shoal Lake and Winnipeg show this depositional break at the base of the upper lacustrine clays, which have in places a maximum thickness of 20 feet. Sections exposed along the Roseau River in southeastern Manitoba also show this break. The evidence shows that the waters of the later lake rose from the lower parts of the Red River Valley to at least the altitude of the main Campbell beach, which was connected with the southern outlet of the lake, and probably somewhat higher.

A moraine which is well developed at Ignace, Ontario, and which extends northwestward for a considerable distance, appears to mark the limit of the latest advance of the ice-sheet in this region, and also to mark the border of the second Lake Agassiz at the time of its maximum extension.

The acceptance of the present view regarding the life history of Lake Agassiz has an important bearing on the question of the character and cause of the differential uplift, which is shown to have affected the region by the deformation of the shorelines. The direction of maximum uplift agrees very nearly with the direction of advance of the ice from the northeast, but not with that of the Keewatin ice-sheet. The whole southern portion of the lake basin, as well as the northern portion, was affected by uplift, as was shown by Upham.

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[1] Presented with the permission of the Director of the Geological Survey of Canada.

A large part of the uplift took place during the existence of the later lake, and a large area beyond the margin of the ice-sheet was affected. If the uplift was due to isostatic recovery following relief from the burden of the ice-sheets, as is generally held, it is evident that uplift must have "lagged" behind the removal of the main mass of the Wisconsin ice-sheet.

DISCUSSION

Prof. **FRANK LEVERETT** spoke of the importance of the work of Mr. Johnston in throwing light on the closing part of the Wisconsin stage of glaciation, and especially in its suggestion of a second or later Lake Agassiz, formed by a readvance of ice from the northeast which blocked the drainage to Hudson Bay. The first Lake Agassiz loses none of its importance, however, because of the recurrence of the ponded condition in the Lake Agassiz area. It is probable that the southern outlet through the Minnesota Valley, known as River Warren, was cut nearly to its full depth by the discharge from the earliest lake. Mr. Warren Upham's interpretations, as given in the monograph on the Glacial Lake Agassiz, seem, therefore, to need merely a supplementary chapter rather than a radical modification.

The Secretary read a letter from Warren Upham as follows:

"It is quite evident that W. A. Johnston, of the Canada Geological Survey, has a strong 'courage of his convictions' for his papers on Lake Agassiz; but I feel entirely sure that his main contention is an error, and I hope that good discussion by members present, following his paper, and also after Keyes' paper on Lake Bonneville, will adequately defend whatever there is of truth of Gilbert's and my United States Geological Survey monographs.

"The grand evidence that the melting ice-sheet lay close against each side of Lake Agassiz, while it grew from south to north, is the derivation of the sand and gravel of the great deltas on the east and the much greater deltas on the west, these deposits being surely supplied in such localized abundance by drainage from the drift-covered melting ice-border.

"It is objected that the lake area should show boulders dropped from bergs, but I believe that the melting in rapid progress by surface ablation of the ice-sheet gave no conditions for detachment of bergs."

Mr. **J. B. TYRRELL**: It gives me much pleasure to know that the work which Mr. Warren Upham and I did some years ago on Lake Agassiz is now being followed up, and I trust that it may be Mr. Johnston's good fortune to continue to study and elucidate the history of this great postglacial lake, not only in its higher stages, when it discharged southward, but in its lower stages of growth and decline, when it discharged into or was connected in some way with the arctic waters of Hudson Bay.

During the past summer I had the opportunity of traveling over the Hudson Bay Railway from The Pas, on the Saskatchewan River, to mile 295, which was as far as the rails were laid at that time, and some brief notes of the Lake Agassiz deposits observable along the line of the railway may be of interest here.

The town of The Pas is built on a strong gravel ridge, one of the old shores of Lake Agassiz, with an elevation of 880 feet above the sea. Two miles farther north is another somewhat higher ridge of gravel, with an elevation of 924 feet above the sea. At mile 31 on the railway a ridge, the summit of which is 904 feet above tide, shows gravel 16 feet in depth. At mile 109, at the foot of a slope facing toward the north, is a strong gravel beach, with a thickness of 22 feet of gravel. Its summit is 848 feet above tide. At mile 127 a gravel ridge was reported to me by the chief engineer as occurring a few miles to one side of the right of way. The gravel in it was 20 feet thick and the summit of the ridge is 805 feet above tide.

From here northward for many miles the country is covered with well stratified clays of Lake Agassiz, though near mile 157 there was reported to be a light gravel ridge, the crest of which was 731 feet above tide. Thence to the bridge across Nelson River, at mile 241, the country is gently undulating, without any marked elevation, and is covered throughout by evenly and regularly stratified beds of clay. Two miles before reaching the bridge the underlying granite was observed at a place where it had been recently stripped of its covering of soft clay. Consequently its surface was not weathered and it was almost everywhere scored by glacial grooves and striæ of the last Labradorean glacier running true west. In sheltered depressions there were also grooves and striæ of an earlier glaciation running south 40° west. In these depressions the surface showed no signs of weathering.

From the crossing of Nelson River the railway runs eastward. At mile 245 the stratified clay is still several feet in thickness, but ten miles farther east, at mile 255, it had almost disappeared. Near this place an esker makes its appearance and extends eastward as a prominent gravel ridge. From it the railway is obtaining a much needed supply of gravel for ballast. The height of the top of this esker is about 750 feet above tide. Hence eastward the land is a vast level plain underlain by a stony till containing many irregular boulders, and is usually covered with a mantle of bog moss several feet in thickness.

Here, therefore, about 14 miles east of the Nelson River, and at an elevation of 700 to 750 feet above tide, was the eastern shore of Lake Agassiz, when its waters last washed against the foot of the Labradorean glacier. The glacier had previously extended farther westward into the basin of the lake, as we have seen from the grooves and striæ on the rocks west of the Nelson recorded above, and also from other records given in my report, written in 1896 and published in 1902, on "The northeastern portion of the district of Saskatchewan," which country is now mostly included within the province of Manitoba. Whether at any earlier period, in its advance westward, the Labradorean glacier reached the eastern shore of Lake Agassiz at some place farther east than this and afterward plowed away or overrode such lacustrine beds as may have been deposited in front of it in the lake is not known.

Proceeding eastward over the till-covered plains, at mile 286, where the track has an elevation of 630 feet above tide, a well washed sandy esker rises to a height of 45 feet above the general level and extends east and west for a considerable distance. On its surface are scattered a few boulders from one to two feet in diameter. At mile 295, at an elevation of 558 feet above tide, is a little sand ridge in which some of the pebbles are fairly well rounded. It has somewhat the appearance of an old beach ridge, and if so it may represent the highest old shoreline of Hudson Bay in postglacial times.

This was the end of the track at the time of my visit, but the chief engineer informed me of a very strong gravel ridge at mile 330, whose crest is 430 feet above tide. This ridge may be regarded with certainty as one of the old shores of Hudson Bay. Other old raised shores occur along the railway location between that place and Port Nelson, at mile 424. I saw no evidence of the presence of a moraine at or near the eastern limit of the Lake Agassiz clays.

ROCK TERRACES IN THE DRIFTLESS AREA OF WISCONSIN

BY LAWRENCE MARTIN

(*Abstract*)

In working out the physiography and stratigraphy of the Tomah and Sparta quadrangles, Wisconsin, for the State Geological Survey, a system of rock terraces was mapped in 1916 by the author, assisted by F. T. Thwaites. These are in the western upland of Wisconsin, within the driftless area, near the headwaters of the Kickapoo, Lemonweir, and La Crosse rivers, a few miles east of the Mississippi. The rocks in the district include: (*a*) Oneota (Lower Magnesian) limestone which caps ridge tops in the broad Magnesian cuesta; (*b*) two cliff-makers in the Saint Croix (Potsdam) group—an upper on the Jordan sandstone, a lower on the Dresbach sandstone; (*c*) two weaker, terrace-capping formations between these—the Saint Lawrence and the Franconia.

The Saint Lawrence terrace and one of the Franconia terraces are the two persistent topographic features within the valleys of the area. There are often four or five terrace steps, the main Franconia terrace being wide enough so that the escarpment at the border of the western upland is usually double, with cliffs and steep slopes of Dresbach and Jordan at the borders of the Franconia terrace and Magnesian cuesta respectively. Likewise the Kickapoo Valley is double, or benched, the Franconia terraces making broad upper shelves, as if a narrower valley had been intrenched below the level of a broader strath. It seems certain, however, that there has been no halt and subsequent uplift in connection with the formation of this and the other terraces, as Butts implied in the original technical use in Pennsylvania of Geikie's Scotch term *strath*.

The terraces and the cliffs in Wisconsin are due to weathering of unequally resistant sandstones. The cliff-making sandstones are coarse grained and thick bedded, the Jordan being case hardened at the top, the Dresbach likewise having the firmest layers above. The terrace sandstones are fine grained, the Saint Lawrence approaching limy shale near the base, and the Franconia being glauconitic, with micaceous sandy shale forming a rather impervious capping for the underlying Dresbach. That the minor features of topography are controlled by rock structure is another argument, not independently decisive, to be sure, but to be added to those[1] which lead to the interpretation of the upland near the Mississippi River in Wisconsin and adjacent States as cuesta rather than dissected peneplain. A reconnaissance of a considerable

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[1] Bull. 36, Wis. Geol. and Nat. Hist. Survey, 1916, pp. 63-70.

number of other valleys in the driftless area reveals the same rock terraces, the lower ones occasionally preserving chert gravels which do not seem to necessitate earlier cycles of erosion.

Presented by title in the absence of the author.

PLEISTOCENE DEPOSITS IN THE SUN RIVER REGION, MONTANA

BY EUGENE STEBINGER AND MARCUS I. GOLDMAN

(*Abstract*)

This paper describes the southward extension to and beyond Sun River of phenomena observed by W. C. Alden and others in the vicinity of the Glacier National Park in 1911 and 1912. Deposits of the later (Wisconsin) stage of mountain glaciation in this region and the variations in the plainsward extension of the different glaciers of this epoch are first described. The high level gravels on flat-topped ridges, remnants of the Blackfoot peneplain in this region, are then discussed. The absence of definite evidence of pre-Wisconsin glaciation in these gravels is probably due to one or both of two causes: (1) A relatively slight extension of the glaciers on the plains, similar to that during the Wisconsin stage, so that the glacial deposits were not laid down beyond the area of erosion of the active mountain streams; (2) the absence in the mountains glaciated of the compact, fine-grained argillites of the Glacier Park section, so well suited to the preservation of glacial markings. On account of these facts the absence of high level glacial deposits is not believed to indicate the absence of the older glaciation in this region. Map of the area described will be placed on exhibition.

Presented by title in the absence of the authors.

LARGE ROCK SLIDE IN THE WIND RIVER MOUNTAINS OF WYOMING

BY E. B. BRANSON

(*Abstract*)

A large rock slide, four to five miles long by one-fourth to one-half mile wide, occurs in Bull Lake Creek Canyon, in the Wind River Mountains, 50 miles northwest of Lander, Wyoming. It owes its glacier-like motion to the slumping of great masses of Cambrian and Ordovician limestone on slippery Cambrian shales that dip eastward about 10 degrees.

Presented in abstract extemporaneously.
Brief remarks were made by Prof. G. F. Wright.

SAVING THE SILTS OF THE MISSISSIPPI RIVER

BY WALLACE W. ATWOOD AND RODERICK PEATTIE

(*Abstract*)

Much of that portion of the plain of the lower Mississippi Valley which is not actually swamp is in danger of flood, and is surrounded by wide stretches

of unhealthful waste lands. The manipulation of the Nile floods, as well as certain experiments now in progress on the Illinois bottom lands, and the work actually accomplished in reclaiming river floodplains in Europe, suggests saving a part, at least, of the Mississippi River silts, and with them building up the low places in the great floodplain.

Certain favorable areas might be enclosed by levees, and into them the spring floods could be cautiously admitted. By means of two gates a gentle circulation could be established, so as to bring more silt-burdened waters over the land. The floods receding, the land would be drained, and the new layer of soil used for crop raising. This process could be repeated annually until the land should be above the danger of severe floods. The Mississippi carries each year to the Gulf enough silt to cover a square mile to the depth of 268 feet. A portion of this soil might be converted into natural levees, constituting the richest of lands, elevating an area out of the reach of disastrous floods, reenforcing the artificial levees, vastly improving the health conditions of portions of the valley, and tending to regulate the flow of the river in times of danger. Possibly, in time, the entire floodplain of the Mississippi River would be reclaimed for agriculture. Judging from previous improvements, the return would be far greater than the expenditure.

Presented in abstract extemporaneously by the senior author.

DISCUSSION

Mr. E. W. SHAW: There is, of course, no question but that the building up of floodplains, whether a natural, an artificial, or a combination process, is often profitable to man in the long run if not immediately. It has been my good fortune to see examples in the United States, Europe, and Egypt, and also to see a good deal of the lower Mississippi and its floodplain, which is by no means free from either variety of upbuilding. Indeed, I think I have seen some places where artificially controlled silting to bring the surface above floods was done before white men came to the country.

There is also, of course, no question but that it would be possible to build up the floodplain until it would be higher than the highest recorded flood stage. But that it would be a practical solution of the flood problem at present or in the near future I very much doubt, for several reasons. The Mississippi is a giant and in some respects a peculiar stream, and few people realize what it means to modify its natural habits. One of the principal difficulties would be to catch enough silt to amount to anything and yet transport it for many miles out over the floodplain. In the natural overflows the bulk of the deposition occurs on the natural levee and the total deposit at a distance of more than a mile or two is, as one farmer put it to me, "scarcely enough to make a rail slippery." To build up a belt a mile wide on the natural levee where silting would be easiest would cost a huge sum. It seems to me that Professor Atwood is mistaken in his ideas that "the return would be far greater than the expenditure," that the plan he advocates would soon eliminate the cost of the present levee system, and that it could readily be made immediately beneficial to the soil. Moreover, the opposing sentiment from farmer and navigation to be overcome would be enormous. The land is now fertile, and where silting has occurred the farmer finds it, instead of beneficial, almost as damaging as scour. Finally, if all the silt of the river were caught and spread over the floodplain, it would take literally centuries to build the land up above the present high-water mark, and perhaps by that time the natural high water would be still higher.

On the other hand, as I have traveled about over the bottom lands I have frequently allowed myself to dream of a system of low and gradually raised cross-levees that would catch a considerable part of the silt. It costs but a small fraction as much to build a levee one-third of a foot high as it does one twenty feet high. Such levees are needed for highways anyway. Modern dredges, which move silt thousands of feet at low cost, could be called in to aid in the processes of silting and levee building. Several other beneficial effects might be noted, but at the end of every such dream I have had to admit that the most carefully devised plan would be almost, if not quite, chimerical.

Further remarks were made by Professor Lane.

"DEEPS" IN THE CHANNEL OF THE LOWER SUSQUEHANNA RIVER

BY EDWARD B. MATHEWS

(*Abstract*)

The purpose of the paper is to present to the Society and place on file certain facts regarding the bottom of the Susquehanna gorge disclosed by soundings and withdrawal of the water incident to the construction of the McCalls Ferry Dam.

The special scientific interest of the phenomena described lies in the fact that these "deeps" lie south of the generally accepted limits of the ice-sheets, in a region of more or less homogeneous rock, which gives little or no evidence that it has undergone sharp warping since the cutting of the river gorge.

These facts and the peculiar features of the "deeps" make the application of the usual explanations for such phenomena doubtful, if not impossible, in the present case.

Presented in abstract extemporaneously.

NEW TEST OF THE SUBSIDENCE THEORY OF CORAL REEFS

BY REGINALD A. DALY

(*Abstract*)

The floors of many atoll and barrier lagoons situated in the trade-wind belts fail to show the transverse profiles expected if the enclosing reefs were formed as Charles Darwin imagined. Where the dominant winds blow from one quarter, the lagoon bottoms should, according to the subsidence theory, be differentially aggraded in the general direction of those winds. But the ocean charts clearly show the lagoons so placed to have practically the same depths to windward and to leeward of their respective centers.

Presented in abstract extemporaneously.

MICROSCOPIC STRUCTURAL FEATURES OF THE BANDED GLACIAL SLATE OF PERMO-CARBONIFEROUS AGE AT SQUANTUM, MASSACHUSETTS

BY ROBERT W. SAYLES [1]

(*Abstract*)

During the last year a microscopic study of the glacial slate at Squantum, Massachusetts, has revealed many features which point to the seasonal nature of the banding. A number of microscopic sections of this banding, taken from specimens from Squantum and several other localities in the Boston basin where this slate is exposed, were exhibited.

A number of photographs, showing in a comparative manner the banded clays of the Connecticut Valley and the Squantum slate, were also exhibited.

Presented by title and discussed and illustrated in the exhibition room.

WEATHERING OF ALLANITE

BY THOMAS L. WATSON

(*Abstract*)

Allanite occurs in many localities in the eastern United States in massive form and fairly abundant. Where found above water-level in the belt of weathering, the lumps and masses of allanite have frequently undergone partial decomposition exteriorly from weathering and are invariably coated partly or wholly with usually a reddish brown crust, at times of lighter color, of variable thickness. In some localities the weathered product exhibits a layered structure—an inner reddish brow layer and an outer lighter colored very thin layer which may be almost white in some specimens. In the larger lumps and masses the thin weathered crust is sharply defined from the larger central mass of fresh mineral.

Some of the more important localities have been studied in the field and collections made of the fresh allanite and its alteration product for laboratory study. Microscopic study of the weathered product from many eastern localities shows it to be heterogeneous in character, composed of an isotropic type and a weakly birefracting type, both variable in physical properties and probably in composition. Likewise the ordinary black, vitreous, fresh allanite is shown microscopically to be a mixture of isotropic and birefracting types, the latter derived from the former either by alteration or by inversion, probably by alteration. Chemical analyses have been made of the fresh allanite and its alteration product from localities in Amhert, Nelson, and Roanoke counties, Virginia, and the changes involved in the transformation from fresh to decomposed mineral are discussed.

Presented by title.

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[1] Introduced by J. B. Woodworth.

ORIGIN OF DOLOMITE AS DISCLOSED BY STAINS AND OTHER METHODS

BY EDWARD STEIDTMANN

(*Abstract*)

That most dolomites were formed in the sea seems to be indicated by the following facts: (1) Dolomites and limestones are frequently interstratified. (2) Dolomitization is often related to original structures, such as bedding, worm borings, etcetera, but rarely to faults and joints and other secondary structures. (3) Chemical analyses of limestones and dolomites, as well as the differentiation of limestones and dolomites by stains, shows that limestones free or nearly free from dolomite, and dolomites nearly free from calcite are vastly more common than beds composed of mixtures of limestones and dolomite. If most dolomites had resulted from the action of underground waters, gradations between limestones and dolomites ought to be common. (4) Calcite fossil casts are often embedded in dolomite. Hollow casts are frequently enclosed by perfect dolomite molds. In either case the calcitic shells evidently were deposited in a dolomite ooze. (5) Perfect dolomite rhombs are sometimes embedded in compact hornlike calcitic beds. It seems more probable that such dolomitic crystals developed when the bed was still in the form of an ooze. (6) Dolomites and limestones have about the same range of porosity. Had dolomites developed dominantly by underground waters, one would expect them to be, on an average, more porous than limestone, for two reasons: (*a*) the porous limestones would be more likely to alter to dolomite because of their permeability: (*b*) from theoretical considerations, the change from calcite to dolomite has been assumed to involve a decrease in volume. (7) If dolomites had resulted *chiefly* from the action of underground waters, they ought to be most abundant in the ancient formations. Both limestones and dolomites, however, are well represented in the pre-Cambrian, and the distribution of dolomites in the rocks of later periods can not be consistently correlated with the length of time to which they have been subjected to the action of underground waters.

The differentiation of calcite and dolomite by stains yields facts which show that replacement is an important dolomitization process. In mixed beds of dolomite and calcite, the dolomite has a bunchy, irregular, sometimes grotesque distribution which disregards the bedding planes and the joints. Dolomitization frequently is local, being adjacent to or within pervious marine structures such as worm borings, shell cavities, etcetera. That dolomite replaces calcite without regard to the crystal boundaries of calcite is indicated by the fact that dolomite grains in contact with calcite are rhombohedral; the calcite grains, however, are anhedral. Dolomite rhombs also invade calcitic fossils, but only in the more advanced stages of replacement. They replace calcite by a process of complete reconstruction of the conquered territory. Undigested calcite grains within dolomite rhombohedra or dolomite skeletons were not observed by the writer.

Fossils and the shallow water structures of most dolomites show that, like most limestones, they were laid down in shallow, warm seas. Salinity seems to have favored dolomitization, since the dolomites of certain periods are chiefly in association with the salt beds and not with the contemporaneous open sea beds.

Ferrous oxide seems to be a universal constituent of dolomite. The sedimentary calcite of Mississippi Valley limestone, tested by the writer, showed no ferrous oxide. From their ferrous oxide content it is certain that dolomites were formed under reducing conditions. The absence of ferrous oxide in the primary calcite of limestones suggests a difference in the chemical conditions of limestones and dolomite deposition.

The writer succeeded in differentiating calcite from dolomite with a modified form of the standard Lemberg solution, consisting of 4 grams of fresh $AlCl_3$ crystals, 6 grams extract of logwood, and 1,400 grams of water, boiled for 20 minutes with constant stirring and then filtered. Due to its ferrous oxide content, dolomite turns blue in a dilute HCl solution containing a few drops of freshly prepared potassium ferricyanide. Sedimentary calcite was unaffected by this solution, but most vein calcite turned blue.

Presented in abstract extemporaneously.

SOME FURTHER CONSIDERATION OF THE FORCES DEVELOPED IN CRYSTAL GROWTH

BY ARTHUR L. DAY

Presented in abstract extemporaneously.

PROBLEM OF THE ANORTHOSITES

BY N. L. BOWEN [1]

(*Abstract*)

By reason of their occurrence almost exclusively in the ancient terranes, of their great size, and of their comparative uniformity of composition over wide areas, the anorthosites present a number of problems to the petrologist. But it is perhaps more in virtue of their simple composition that the anorthosites may be said to present a special problem. Normally, rocks are made up of several minerals, and when considering their magmas we have come to regard the various minerals as existing therein in mutual solution. Thus, though minerals as individuals are often among our most refractory materials, magmatic temperatures, or the temperatures of mutual solution, are believed to be, and for very good reasons, comparatively moderate. What, then, of the solution theory as applied to anorthosites which, typically, consist almost exclusively of the single mineral plagioclase? Were they ever hot enough to be molten *per se?* Chemical considerations and field facts both indicate that this latter question is probably to be answered in the negative. The chemical considerations bring out the improbability of the formation of anorthosite in any manner other than by the accumulation of plagioclase crystals precipitated from solution in a mixed magma, and therefore the probability that anorthosites were never molten as such. The field relations of the anorthosites, as recorded by numerous observers, seem to be entirely consistent with this view of their origin.

An examination of the anorthosites of the Adirondack area and of the Morin area with this aspect of the question especially in mind has strengthened the

belief that this interpretation of the origin of anorthosites is substantially correct. A conception of the Adirondack anorthosite-syenite complex as essentially a stratified mass, with syenite above and anorthosite below, together with the evidence favoring this conception, were offered for consideration.

Presented in abstract extemporaneously.

Discussion

Dr. F. D. **Adams**: Doctor Bowen has asked those members who have studied anorthosites in the field for information on two points: First, Do anorthosites occur in small dikes? and, second, Do these rocks commonly display protoclastic structure? Having examined a number of the anorthosite areas of the Canadian shield, I may say that I cannot remember any occurrence of anorthosite in a form of a small dike, while on the other hand protoclastic structure is widespread in many, if not all, of the areas in question.

Mr. J. A. **Dresser**: Bordering the great anorthosite area of the Saguenay district on the south, there is a large development of syenite in the vicinity of the Saguenay River. The detailed relations have not been worked out, but the field evidence, as far as known, suggests strongly that on approaching the anorthosite the syenite grades into a granite which is plainly intrusive into the anorthosite.

Further remarks were made by Professors Cushing and Graton.

CLASSIFICATION OF METAMORPHIC ROCKS

BY WILLIAM J. MILLER

(*Abstract*)

A comprehensive classification of metamorphic rocks was presented, the main principles of which are based on origin and structure, and these principles were discussed. The attempt has been made to work out a satisfactory classification without the introduction of new terms.

Presented in abstract extemporaneously. Discussion put into exhibition room for 4 o'clock.

RELATIONSHIP BETWEEN THE IGNEOUS AND METAMORPHIC ROCKS OF THE DISTRICT OF COLUMBIA AND VICINITY

BY C. N. FENNER

(*Abstract*)

The rocks of this region consist of a series of chloritic, sericitic, and micaceous schists and gneisses (grouped by the U. S. Geological Survey as Carolina gneisses), associated with bodies of massive to gneissoid igneous rock, generally of the composition of diorite or granite. Many of the bodies of undoubtedly igneous character show an abundance of inclusions of foreign material, and

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[1] Introduced by C. N. Fenner.

the distinctly foliated gneisses also are frequently so filled with inclusions as to suggest a conglomeratic origin. In an endeavor to work out the explanation of these features, evidence has been found which points distinctly to a derivation of the igneous masses (in large part at least) from the previously formed schists. The nature of the evidence was described and a series of polished specimens was exhibited, illustrating certain prominent features resulting from the operation of the processes, such as the initial localized softening of the country rock and successively later stages of disintegration and fusion; the manner in which inclusions in the magma become shredded and assimilated; effects of diffusion in producing banded structure in inclusions; the straining off of liquid magma from suspended matter; the production of gneissic foliation from the parallel orientation of suspended shreds, etcetera.

Presented in abstract extemporaneously.

PRECAMBRIAN SEDIMENTARY ROCKS IN THE HIGHLANDS OF EASTERN PENNSYLVANIA

BY EDGAR T. WHERRY

(*Abstract*)

The Precambrian rocks of the highlands of Pennsylvania include several formations of sedimentary origin, in part not heretofore recognized. These comprise crystalline limestone, quartz-mica schist, graphite-bearing quartzite, and several types of gneiss. The petrographic characters of these formations are described and the mineralogical and structural criteria indicating their sedimentary origin discussed. Injection, feldspathization, and assimilation are shown to have been effective in developing gneisses from the sedimentary rocks.

Presented in abstract extemporaneously.

At this point recess was taken.

The Society reconvened at 2.30 o'clock. President Clarke, presiding, announced that the regular program for the afternoon would begin with a Symposium on the Geology of Petroleum, as follows:

GENERAL GEOLOGICAL CONDITIONS AND FUTURE SUPPLY

BY RALPH ARNOLD

In the absence of the author, this paper was read by Doctor Clarke.

APPALACHIAN OIL FIELDS

BY M. L. FULLER

ILLINOIS OIL FIELD

BY FRED H. KAY

OHIO-INDIANA OIL FIELD

BY J. A. BOWNOCKER

PACIFIC COAST OIL FIELD

BY R. W. PACK

MID-CONTINENT OIL FIELDS

BY JAMES H. GARDNER

ROCKY MOUNTAIN OIL FIELDS

BY F. A. FISHER

This paper was read by title.

GULF COAST OIL FIELD

BY G. D. HARRIS

This paper was read by title.

CANADIAN OIL FIELD

BY W. G. MILLER

PRODUCTIVITY OF OIL SHALES

BY DAVID T. DAY

This paper was read by title.

PRACTICAL APPLICATION OF GEOLOGICAL STRUCTURE THEORIES TO OIL RECOVERY

BY I. C. WHITE

LATEST THEORIES REGARDING THE ORIGIN OF OIL

BY DAVID WHITE

TITLES AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE AFTERNOON SESSION AND DISCUSSIONS THEREON

At the conclusion of the papers constituting the symposium those on the regular list relating to the same subject were presented as follows:

ETHICS OF THE PETROLEUM GEOLOGIST

BY FREDERICK G. CLAPP

(Abstract)

The question of professional ethics arises sooner or later in every profession and must be met and answered by every individual for himself; but in his decisions he is naturally guided to a great extent by the practices of his fellow-engineers and by the relations in which he is placed toward his clients, associates, and the public. In the older professions ethical considerations have been generally recognized for many years, and this is true to a considerable extent of the consulting engineer at large. Petroleum geology, however, is such a new profession that some questions arise repeatedly, without bringing

satisfactory answers. The writer of this paper undertakes to consider a few points which have arisen in his own experience and that of his associates, trusting that the paper will secure discussion which will warrant tacit recognition by the Society of a suitable code of ethics for petroleum geologists.

Presented in abstract from notes.

REVISION OF STRUCTURAL CLASSIFICATION OF PETROLEUM AND NATURAL GAS FIELDS

BY FREDERICK G. CLAPP

(*Abstract*)

The original paper, which proposed a "Classification of petroleum and natural gas fields based on structure," was published in Economic Geology in 1910, having been presented in brief before the Geological Society at Washington earlier in the same year. During the intervening six years geological examination of oil fields has grown from a new branch of engineering into one which is now generally recognized as essential to efficient oil development. Few real changes have been necessary in the classification as originally proposed, but a number of additions have been made, and it has lately been necessary to further subdivide the classification. In the present paper this is carried as far as is practicable at the present time; and, to make the classification comprehensive, a large number of additional examples are given of fields where the respective types of structure exist.

Presented in abstract extemporaneously.

INTERMOLECULAR ATTRACTIONS AND OIL AND GAS ACCUMULATION

BY EUGENE WESLEY SHAW

(*Abstract*)

A review of the literature discussing the ages of the widely known peneplains of the Appalachian province brings out the fact that notions concerning their age are discordant, and an examination of published and unpublished data leads to the inference that the peneplains are as young or younger than the latest date so far assigned. For example, the so-called Cretaceous peneplain is assigned by various writers to pre-Cretaceous, Lower Cretaceous, Upper Cretaceous, and early Tertiary time. The best basis for dating surfaces regarded as remnants of this peneplain seems to be obtained (1) by correlating them with unconformities or deposits in the coastal plain and (2) by the amount of erosion to which they have been subjected. The result seems to suggest that such surfaces are not much older than Middle Tertiary.

Presented in abstract extemporaneously.

RELATION OF STRUCTURE TO THE PRODUCTION OF OIL AND NATURAL GAS IN THE MID-CONTINENT FIELD

BY CHARLES N. GOULD

Presented in abstract extemporaneously.

ORDOVICIAN STRATA BENEATH THE HEALDTON OIL FIELD, OKLAHOMA

BY SIDNEY POWERS[1]

(*Abstract*)

The Healdton oil field in the western portion of Carter County, southern Oklahoma, is situated in "Red Beds" of Permian age, 12 miles from the Pennsylvanian strata which border the Arbuckle Mountains. The oil in the Healdton field occurs largely in Permian sands near the base of this formation, but it may have been derived, according to Wegemann and Heald (United States Geological Survey, Bulletin 621, page 26), from underlying Pennsylvanian or older rocks. In the Loco gas field, Stephens County, Pennsylvanian fossils have been found in drill cuttings, indicating that the pronounced unconformity of the Permian with the older Paleozoic strata which exists around the Arbuckle and Wichita Mountains and the Criner Hills extends beneath the Red Beds of southern Oklahoma.

Fossils from the Hammon and Colcord well number 11, center section 15, township 4 south, range 1 west, Carter County, "shot" from a depth of 1,275 to 1,300 feet, and from the Producers Oil Company well number 11, on the eastern side of the southeastern quarter of the same section, at a depth of 1,550 feet (under-roming specimens), have been identified by Dr. E. O. Ulrich of the United States Geological Survey as of Ordovician age.

Pronounced unconformities must exist beneath several of the southern Oklahoma oil fields in order to account for the pre-Permian rocks at Healdton and Loco and to account for variations in the well logs.

Presented in abstract extemporaneously.

Brief remarks were made by Dr. I. C. White.

At this point the reading of papers was discontinued until the following morning.

PRESIDENTIAL ADDRESS

At 8.15 o'clock Thursday evening there was given in Chancellor's Hall the public address of the retiring President entitled

THE PHILOSOPHY OF GEOLOGY AND THE ORDER OF THE STATE

PRESIDENTIAL ADDRESS BY JOHN M. CLARKE

The address is printed as pages 235-248 of this volume.

At the close of the lecture opportunity was given to visit the Museum, and most of the members later attended the smoker given at the University Club.

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[1] Introduced by J. E. Wolff.

SESSION OF FRIDAY, DECEMBER 29

The Society reconvened at 9 o'clock on Friday morning for the reading of papers, President Clarke presiding.

TITLES AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE MORNING SESSION AND DISCUSSIONS THEREON

DEVELOPMENT OF THREE SUCCESSIVE PENEPLAINS IN KANSAS

BY J. W. BEEDE

(*Abstract*)

1. A pre-Dakotan peneplain extends westward from the east-facing Flint Hills escarpments and passes beneath the Comanche-Dakota rocks, north of the latitude of Great Bend, and grades into the Great Bend lowland south of that latitude, north of the Arkansas River. It also begins with the Gypsum Hills escarpment and extends westward to the Comanche and Tertiary deposits southwest of the Great Bend lowland in Kansas and Oklahoma. Both of these regions are low plateaus and they are designated the Dwight and Ætna plateaus respectively.

2. The Cretaceous sediments of Kansas were peneplained prior to the deposition of the Pliocene sediments of western Kansas, and this peneplain is now represented by the high divides of the central third of the State, and the divides and valleys of the western edge of the State, north of the Arkansas River. Much of this area is covered with Tertiary sediments. This peneplain is designated the Paradise peneplain.

3. Later a broad peneplain was developed within the Paradise plain, apparently before the deposition of the early Pleistocene sediments of the Great Plains. It varies from three or four miles to twenty miles in width with the nature of the rocks of the region. This feature is designated the Wilson peneplain and is regarded as latest Pliocene age.

4. East of the Dwight Plateau two similar peneplains were developed that seem to be continuous with the Paradise and Wilson peneplains along the valley of the Smoky Hill River, and the two sets are regarded as identical.

Presented by title in the absence of the author.

HYPOTHESIS FOR THE RELATION OF NORMAL AND THRUST-FAULTS IN EASTERN NEW YORK

BY GEORGE HALCOTT CHADWICK

(*Abstract*)

A theory is presented of the secondary or corollary relation of the Adirondack-Mohawk step-faults to the great charriage movements of New England over eastern New York, which, by overloading, may have depressed successive fragments of the overridden area. The sedimentary contact of the Cobleskill limestone on the translated mass of Normanskill shale at Catskill is cited as proof of the early date at which this thrusting was initiated, and the similar

displacements in the superjacent Devonian strata as indicative of its repetition or persistence later. An attempt is made to show the probable presence of more of these overthrusts eastward in the metamorphic belt of western New England, which would seriously affect some of the current correlations.

Presented in abstract extemporaneously.

DISCUSSION

Prof. B. K. EMERSON: Very similar overthrusts of Cambrian and pre-Cambrian cover the Stockbridge limestone (Ordovician) along a north-south line, running across the State on a line west of Pittsfield-Williamstown. Vertical north-south faults appear in the limestones underlying this overthrust, and in Dalton a series of shallow artesian wells has supplied the pure water that has made the paper mills there so successful. The weight of the overthrust beds has not been thought adequate to explain so extensive vertical faulting in Massachusetts.

Prof. W. J. MILLER: I believe Professor Chadwick has given a very suggestive explanation of the causes of the extensive normal faulting of the eastern Adirondacks. So far as I know, after some years of field-work in that region, the main facts regarding the faults mostly harmonize with the hypothesis offered. There is considerable evidence, however, that much of the faulting, or at least renewed faulting along old fracture lines, has taken place since the great overthrusting from the east and even since the removal of the overthrust mass by erosion, and it is not clear to me how this relatively recent faulting is to be accounted for by Professor Chadwick's hypothesis.

Reply was made by the author.

EVIDENCE IN THE HELENA-YELLOWSTONE PARK REGION, MONTANA, OF THE GREAT JURASSIC EROSION SURFACE

BY D. DALE CONDIT

(*Abstract*)

A wide-spread baseleveling over most of the Rocky Mountain region preceded the deposition of Jurassic sediments. Evidence of this in the Helena-Yellowstone Park region is presented. From the Idaho State line northward to the vicinity of Helena this erosion surface truncates beds ranging in age from Triassic to carboniferous (Quadrant formation), some 1,000 feet lower stratigraphically.

Presented in abstract extemporaneously.

"GIANT RIPPLES" AS INDICATORS OF PALEOGEOGRAPHY

BY WALTER H. BUCHER[1]

(*Abstract*)

Objections are presented to the current interpretation of the "giant ripples" in the Ordovician as wave-formed (oscillation) ripples. Their formation by

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[1] Introduced by N. M. Fenneman.

currents of constant direction is discussed; they are contrasted with current-marks and sand-waves. Field evidence is given to the effect that the only current to which the formation of the Ordovician and Silurian "giant ripples" can be ascribed is the tidal current.

The horizontal distribution of these ripples in the Silurian of the Cincinnati anticline is contrasted with that of the Ordovician of the same area, and the peculiar geographical conditions necessary for the production of each are discussed. The rhythmic recurrence of the different sedimentary units, characteristic for the Ordovician of this region, is explained and the depth of the corresponding ocean determined to be less than fifteen fathoms.

Discussion

Prof. A. W. **Grabau**: Two points have always puzzled me about fossil ripple-marks. The first: How can beach ripples and those made by tidal currents and exposed between tides be preserved when every succeeding tide or wave will obliterate the older series and make a new one? The other is this: How can we understand the total absence of fragments of organic remains in such beautifully ripple-marked sandstones as those of the Berea and Bedford of Ohio if these formations are marine? Rippled beach sands, and especially rippled sands of deeper water in the modern ocean, always contain some vestiges of organic remains.

Prof. G. H. **Chadwick**: In the Mohawk Valley, just after one of its largest floods, there was observed a remarkable series of gigantic current ripples in mud, whose crests, perhaps 15 or 20 feet apart, showed above the subsiding waters. It should not be forgotten that the first use of the name "giant ripples," by Gilbert, had reference chiefly to a wholly different phenomenon, the isolated "beach-crests" of the Medina sandstone, later more fully explained by Fairchild.

Further remarks were made by Prof. C. H. Brown, with reply by the author.

At 10 o'clock the reading of miscellaneous papers was discontinued and place given for the Symposium on the Interpretation of Sedimentary Rocks, under the titles which are given below:

THE PROBLEMS STATED

BY A. W. GRABAU

SIGNIFICANCE OF SEDIMENTARY RHYTHM

BY JOSEPH BARRELL

DIAGNOSTIC CHARACTERISTICS OF MARINE CLASTICS

BY E. M. KINDLE

CHARACTERISTICS OF CONTINENTAL CLASTICS AND CHEMICAL DEPOSITS

BY ELIOT BLACKWELDER

SIGNIFICANCE OF SORTING IN SEDIMENTARY ROCKS

BY E. W. SHAW

CHEMICAL AND ORGANIC DEPOSITS OF THE SEA

BY T. W. VAUGHAN

At the conclusion of the symposium the reading of miscellaneous scientific papers was again taken up.

DEFORMATION OF UNCONSOLIDATED BEDS IN NOVA SCOTIA AND SOUTHERN ONTARIO

BY E. M. KINDLE

(Abstract)

The paper describes certain contorted beds in postglacial deposits which lie between undisturbed horizontal beds. Photographs of water-laid beds formed under laboratory conditions in which the features found in nature are duplicated were shown. These experiments show a high degree of contortion and disturbance in the upper beds of a section which was developed in an experimental tank. This deformation was produced by differential weighting with sand and shot, and shows that the upper beds of a section may be greatly disturbed by this means without producing any disturbance of the lower beds. The explanation of the contorted beds on the Avon River, in Nova Scotia, was deduced from these experiments and referred to differential weighting by superior beds, which were later removed by current scour.

The disturbed beds which were described in old lake deposits on the north shore of Lake Erie were attributed to the action of stranded icebergs and floating ice in disturbing the bottom deposits of the glacial Lake Whittlesey.

Read in abstract from manuscript.

ILLUSTRATIONS OF THE DEFORMATION OF LIMESTONE UNDER REGIONAL COMPRESSION

BY DAVID H. NEWLAND

(Abstract)

The Grenville limestones in the vicinity of Port Henry, New York, afford numerous examples of folding of intense character, which is brought out strikingly by the included amphibolite bands that have participated in the process. The limestone shows accommodation to pressure by plastic flowage, while the harder rock has suffered fracture and dismemberment.

Presented in abstract extemporaneously.

Brief remarks were made by Mr. Arthur Keith.

SILVER CITY QUARTZITES, A KANSAS METAMORPHIC AREA

BY W. H. TWENHOFEL

(*Abstract*)

Silver City, Kansas, an abandoned mining camp, is underlain by altered sedimentary rocks, which consist chiefly of quartzites; but one member of the sequence is a breccia, the cement of which is composed of quartz, chlorite, and hornblende. The altered area is about 200 yards wide and less than a mile long. The surrounding strata are unmodified.

The evidence leads to the conclusion that the change is due to hydrothermal action.

The occurrence is of interest because of the rarity of metamorphic rocks within that section of the country.

Presented in abstract extemporaneously.

OROGRAPHIC ORIGIN OF ANCIENT LAKE BONNEVILLE

BY CHARLES R. KEYES

(*Abstract*)

A recent inquiry into the derivation of certain features of the Great Basin, Great Salt Lake, and especially its precursor, the vaster Lake Bonneville, presented some seeming anomalies which, from a perusal of the literature alone, could not be readily adjusted to the modern genetic scheme of physiographic development. This circumstance eventually led to several special visits to the Utah field and a critical examination on the ground of the published data relating to the geologic history of the old desert lake. In the prevailing hypothesis concerning the origin of Lake Bonneville so many incongruities were found as to compel its abandonment. Instead of a genesis due to conditions of moister climate induced by a glacial epoch, the facts gathered seemed to point not only to a pre-glacial date of the lake's birth, but to a diastrophic, rather than a climatic, cause for the lake's existence.

The conclusions reached are that the great body of water of which Great Salt Lake is a last vestige is not, after all, an anomaly among desert features, but that it merely represents a special phase of a through flowing stream that was not quite large enough to master the orogenic barrier which chanced to arise athwart its path, while its nearest neighbor and parallel stream, the Green River, reinforced by the Grand and other large eastern tributaries, was sufficiently powerful to hold its own against all vicissitudes and to carve through the rapidly bulging Colorado dome a Titan among chasms. Blocked by such a formidable rampart, the old Virgen River spread out far and wide over the adjoining intermont plains. Finally, the principal headwaters being diverted, the waters of the great lake evaporated until equilibrium was again established with the tributaries now greatly reduced.

Presented by title in the absence of the author.

PERSISTENCE OF VENTS AT STROMBOLI AND ITS BEARING ON VOLCANIC MECHANISM

BY H. S. WASHINGTON

(Abstract)

When visited in August, 1914, the crater terrace of Stromboli presented five active vents. Search through the literature has shown that the sites of these foci of activity, with one or two others, have persisted in location for at least about 150 years. This is shown by a series of plans and sketches which go back to 1768 and which are reproduced in the paper. A similar persistence in localization of activity is noted at Kilauea (about 100 years) and at other volcanoes. The vents at Stromboli, as well as some at Etna and Kilauea, are situated near the edge of a high scarp, through the face of which the volcanic activity would presumably have found its way had it been of an explosive character. It appears that the best explanation for the persistence and other characters of the Stromboli, Etna, Kilauea, and other such vents is to ascribe their origin to some such process as that suggested by Daly in his gas-fluxing hypothesis.

Presented by title in the absence of the author.

Printed as pages 249-278 of this volume.

PLEISTOCENE DEFORMATION NEAR RUTLAND, VERMONT

BY ARTHUR KEITH

(Abstract)

Several years ago an extinct glacial lake, Lake Rutland, was discovered by the author in western-central Vermont. Its shores rim the valley around Rutland and have two strongly marked sets of terraces, deltas, and cut benches, ranging in general between 900 and 1,100 feet above sea. The upper set ends where a terminal moraine locates the position of the ice-front in Rutland Valley, but the lower and later set extends beyond the area thus far studied. These shores are tilted to the southwest, and the upper shore is steeper than the lower. The tilting varies much, but averages at least 12 feet per mile for one stretch of 15 miles north and south. This deformation is far greater than that assigned to the later glacial lakes Albany and Champlain. Its close relation to the retreat of the ice-margin shows that the land rose quickly in response to the removal of the ice-load. Other relations are shown between deformation and the local rock structures, which bear strongly on the application of isostasy to continental movements.

Presented in abstract extemporaneously.

Brief remarks were made by Messrs. Taylor, Barrell, Coleman, and Reid.

GEOLOGY OF THE LAU ISLANDS, FIJI

BY WILBUR GARLAND FOYE[1]

(*Abstract*)

The Lau Islands form a group extending for 300 miles along the 179th meridian west of Greenwich, between the 17th and 21st parallels of south latitude. They may be grouped into three classes: (1) islands composed of elevated coraliferous limestone, (2) volcanic islands, and (3) islands composed of volcanic rocks and coraliferous limestone. The latter islands have, in certain cases, a conglomerate of coral and shell rubble mingled with rolled pebbles of the underlying volcanic rock resting on an eroded surface of the volcanic rock. Two hundred to three hundred feet of limestone, often with coral heads in place, overlie conformably this basal conglomerate. Dr. T. W. Vaughan has determined the corals as Pleistocene or Recent in date. The islands have been elevated, therefore, in very recent times. In all the islands of this class visited the limestones rest unconformably on an eroded surface of volcanic rocks. The evidence points to subsidence during the deposition of the limestone.

Certain elevated masses of limestone have been eroded to submarine platforms by atmospheric solution since their uplift. Such platforms, if produced by atmospheric solution alone, should now stand near sealevel, for the feeble wave-action behind a protecting reef can not erode to any great depth below that level. It is significant that 77 per cent of the lagoon depths are between 10 and 20 fathoms. Such depths can only be explained by submergence, and the evidence points to the fact that submergence was the result of actual subsidence.

Presented in abstract extemporaneously.

At 1 o'clock the reading of scientific papers was discontinued and the session adjourned for luncheon.

At 2 o'clock the Society reconvened to take up the reading of scientific papers, Past President Coleman presiding.

TITLES AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE AFTERNOON SESSION AND DISCUSSIONS THEREON

INTRAFORMATIONAL STRUCTURE IN THE ORDOVICIAN LIMESTONE OF CENTRAL PENNSYLVANIA

BY RICHARD MONTGOMERY FIELD[2]

(*Abstract*)

This paper deals with the relative importance of ripple-marks and mud-cracks in interpreting some of the conditions under which the Beekmantown, Stones River, and Trenton limestones were formed.

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[1] Introduced by R. A. Daly.

[2] Introduced by Percy E. Raymond.

Mud-cracks and ripple-marks are much more abundant in the Beekmantown and Stones River formations than has been heretofore supposed. The difficulty of their recognition in certain field sections is probably due to the fact that the beds are rarely exposed to view along the plane of the dip, except when quarries have been opened up along the strike. Illustrations will be given of "mud-cracked" areas in cross-section, and an attempt will be made to show the possible evolution of ripple-marked and mud-cracked areas into "edgewise conglomerates" and intraformational breccias.

Presented in abstract extemporaneously.

DISCUSSION

Prof. A. W. GRABAU: Mr. Field's detailed and careful work on the structures of the Paleozoic limestones is sure to be of much use in the determination of the origin of these deposits. He is to be congratulated on his results.

PLEISTOCENE AND POST-PLEISTOCENE GEOLOGY OF WATERVILLE, MAINE

BY HOMER P. LITTLE[1]

(*Abstract*)

This paper describes the fluvio-glacial, estuarine, and floodplain deposits of Waterville and vicinity.

The main mass of the fluvio-glacial deposits is found in an esker several miles long. Many gravel pits occur along it, and in these are good cross-sections which have been studied in detail.

The esker is bordered by marine clays and sands. These overlap the esker and are separated from its gravels by an unconformity considered due to subaerial erosion. Fossils from these clays have been identified and the localities and altitudes at which they were collected carefully indicated.

The altitude, as determined with the Y level, varied from 121 to 139 feet. Over 25 species of invertebrates were recognized, and 4 genera of land plants. The fauna indicates waters still cooled by melting ice, while the flora shows a climate much like the present.

A river terrace 115 feet above sealevel has been excavated in these older clays and gravels by the Kennebec River. On this the larger part of Waterville is built. A narrow terrace about 35 feet lower is also recognized.

Possible evidence of a readvance of the ice is reviewed, and the conclusion drawn that such an advance can not be shown to have occurred in this area.

The paper closes with an attempt to interpret in detail the history of the region.

Presented in abstract from notes.

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[1] Introduced by E. W. Berry.

AGE AND ORIGIN OF THE RED BEDS OF SOUTHEASTERN WYOMING

BY S. H. KNIGHT[1]

(*Abstract*)

The object of this paper is to set forth some recently acquired data which throws additional light on the age and origin of the red beds as they are developed along the eastern base of the Rocky Mountain Front Range, especially along its northern portions. Evidence of both a paleontologic and stratigraphic nature supports the assigning of the greater portion of the Chugwater formation to the Permocarbonic age. It is now known, especially throughout the Laramie Plains region, that the upper 250 feet of the Chugwater is separated from the underlying portion by a disconformity, and that the portion lying above the break is equivalent to the Dolores formation of southwestern Colorado. The evidence for correlating this upper 250 feet, which has been assigned to the Chugwater, with the Dolores, lies in the presence of a pebble conglomerate composed of small limestone pellets, wood fragments, and fragmentary remains of Triassic vertebrates. This peculiar conglomerate is identical in its lithological and stratigraphical habit with the typical Dolores conglomerate, and it contains similar fragmentary remains.

From the foregoing it is evident that in the northern portion of the Rocky Mountain Front Range the dividing line between the Paleozoic and Mesozoic lies within 250 feet of the top of what has previously been held as Chugwater formation. Owing to the widely different age relationship between the upper and lower portions, as manifest by the difference in the fossil content, I would suggest that the name Chugwater be limited to that portion of the formation which is Permocarbonic in age, and that the upper 250 feet be separated as a distinct formation, to be known as the Jelm formation, from the good exposures of the characteristic bone-bearing conglomerate near the east base of Jelm Mountain.

Evidence in proof of the continental origin of this complex group of sediments is fast accumulating. Numerous field observations now at hand await detailed laboratory study before the problem can be satisfactorily solved.

Presented in abstract extemporaneously.

DISCUSSION

Prof. **Erasmus Haworth**: I would like to ask the author if he considers the cross-bedding shown on the canvass as positive evidence that such formations must have been accumulated and arranged by eolian processes? In the Pennsylvanian of Kansas and some parts of Missouri we have a limestone bed with as plainly marked cross-bedding as those shown. This limestone has massive fossils and is interbedded with other limestones and shales, always considered of massive origin.

Prof. **E. B. Branson**: On the eastern slope of the Wind River Mountains the Chugwater is about 1,500 feet thick and there is a well marked unconformity about the middle. The Popo Agie beds, 60 to 80 feet thick, which are continental in origin, are the first above the unconformity. These beds probably correspond to the ones mentioned by Mr. Knight that occur about 400 feet from the bottom of the Red Beds in southern Wyoming. Sandstones 30 to 100 feet thick and strongly cross-bedded occur about 100 feet above the Popo Agie beds and may be windblown in origin, but all of the rest of the Red Beds in this region seem to be marine. Mr. Knight's observations furnish additional proof of the variety in origin of the Red Beds, but do not prove that they are not largely marine.

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[1] Introduced by A. W. Grabau.

Author's reply to Professor Haworth: In answer to Professor Haworth, permit me to say that if an undoubted marine limestone exhibits cross-bedding similar to the type shown on the screen, then I must modify my ideas as to the significance of cross-bedding. The type of cross-bedding here shown is identical to cross-bedding of the eolian type as described by such authorities as Walther, Huntington, Grabau, etcetera. I question whether the cross-bedding in the Pennsylvanian of Kansas belongs to the same genetic type as the cross-bedding under discussion.

Further remarks were made by Mr. Arthur Keith.

GENERAL STRATIGRAPHIC BREAK BETWEEN PENNSYLVANIAN AND PERMIAN IN WESTERN AMERICA

BY WILLIS T. LEE

(*Abstract*)

Criteria usually applied in intercontinental correlation have thus far failed to establish the limits of the Permian in western America to the satisfaction of all geologists. There is lack of agreement as to the significance of different classes of fossils. In some places, as in the Manzano of New Mexico (Lee and Girty, United States Geological Survey Bulletin number 389), are invertebrates said to be Pennsylvanian and vertebrates (Case, Science, volume 44, page 708, 1916) said to be Permian. In other places there seems to be conflict of evidence between the invertebrates and the plants, as, for example, in the Elmdale, Chase, and Wichita formations and their equivalents in Kansas, Oklahoma, and Texas.

Paleophysiography seems to throw light on the Permian question. Two lines of physical research, structural and lithologic, offer promising results. The upper or red portion of the rocks in New Mexico and elsewhere, assigned with doubt to the Pennsylvanian, is lithologically so different from the lower part, or undoubted Pennsylvanian, that it might properly be given a separate name. These red beds of brackish water and continental origin lie unconformably on marine limestone of undoubted Pennsylvanian age and furnish lithologic and structural evidence of orogenic movement and invigorated erosion in the Rocky Mountain region preceding their deposition.

The apparently conflicting lines of evidence are so involved that in few places do all of them agree on a plane of separation between Pennsylvanian and Permian. Relatively little consideration has thus far been given to physical evidence. However, available data of this kind are sufficiently numerous to indicate that certain unconformities which seem to occur at different hori-

zons may be correlated, and that they may indicate a general unconformity between the true Pennsylvanian and the rocks of questionable age overlying it. The erosional unconformity at the base of the Manzano, the angular unconformity between the Pennsylvanian and Permian in the Arbuckle Mountains, in southern Oklahoma, and comparable relations elsewhere, seem to warrant the belief that these unconformities may be due to a diastrophic movement which appropriately constitutes the division between Pennsylvanian and Permian time.

AMSDEN FORMATION OF WYOMING AND ITS FAUNA

BY E. B. BRANSON AND D. K. GREGER

(*Abstract*)

The main outcrops of the Amsden occur in western Wyoming. Its fauna contains many species characteristic of the Meramecian of the Mississippi Valley, together with some species that foreshadow the appearance of Pennsylvanian types.

Presented in abstract extemporaneously by the senior author.

REMARKABLE GEOLOGIC SECTION NEAR COLUMBIA, MISSOURI

BY E. B. BRANSON

(*Abstract*)

Nine formations, ranging from Lower Ordovician to Middle Mississippian in age, are exposed in a distance of one mile, in bluffs about 150 feet high, along the north side of the Missouri River, near Columbia, Missouri. The total exposed thickness is about 200 feet, and seven of the formations are separated by unconformities.

Presented in abstract extemporaneously.

SATSOP FORMATION OF WASHINGTON AND OREGON

BY J. HARLEN BRETZ [1]

(*Abstract*)

The Satsop formation is a wide-spread fluviatile deposit in the river valleys of southwestern Washington, in the Columbia River Valley for at least 200 miles above the mouth, and in the lower Willamette Valley of northwestern Oregon, and is a coastal deposit exposed at intervals along almost the entire Pacific coast of Washington and Oregon. It exists inland at least as far as the Yakima Valley, a tributary of the Columbia, on the eastern flank of the Cascade Mountains of Washington.

From stratigraphic relations and contained fossils the coastal phase of the Satsop formation is known to be of Quaternary age. In the Coast Range it

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[1] Introduced by R. D. Salisbury.

lies in the river valleys; in the Cascade Mountains it is folded into the anticlines of the range, rising from sealevel on the west to a maximum of 4,000 feet above tide and descending on the east nearly to sealevel. This portion of the Cascade Mountains, therefore, is younger than the Satsop formation.

Presented in abstract extemporaneously.

GEOLOGY OF THE AREA OF PALEOZOIC ROCKS IN THE VICINITY OF HUDSON AND JAMES BAYS, CANADA

BY T. E. SAVAGE AND F. M. VAN TUYL

(*Abstract*)

The Paleozoic rocks occurring in the vicinity of Hudson and James Bays include representatives of the Ordovician, Silurian, and Devonian systems. The Ordovician strata of this region embrace limestones corresponding in age to the Galena and the Maquoketa of the Mississippi Valley. In the Galena strata there is a remarkable mingling of Galena types of fossils with genera of corals usually considered characteristic of the Silurian system, and this is true, also, but to a less extent of the Maquoketa fauna. In the Silurian rocks of this district there occur unusually well developed domes or reefs of limestone composed of Stromatoporoid masses, but also containing many species of true corals and other fossils. The Silurian limestones found in this region are all of Niagaran and possibly some of pre-Niagaran age. Devonian rocks were studied only along the Moose and Abitibi rivers. In these localities rocks of Upper and Middle Devonian age are present. The Upper Devonian strata consist of black shale containing numerous spores of *Sporangites huronensis*, overlying a calcareous shale yielding a few brachiopods and corals. The Middle Devonian rocks here correspond to the Hamilton or late Middle Devonian of the Dakota or "Northwest" province.

Presented in abstract extemporaneously by the senior author.

DISCUSSION

Prof. **ERASMUS HAWORTH**: I would like to ask Professor Savage what he meant by the term "Northwest," which he used a number of times. I suppose he referred to some specific area; but what area?

Mr. **M. Y. WILLIAMS**: Are there any bituminous beds in the Silurian section?

Prof. **G. H. CHADWICK** asked Professor Savage if his Niagaran section included any "Cataract."

In reply to Professor Haworth, the author remarked: The area of late Middle Devonic of Iowa, Manitoba, and farther northwest.

In reply to Mr. Williams: There are none.

In reply to Professor Chadwick: I can not state definitely until we have carefully studied our fossil collections. However, from our impressions in the field, I am expecting to find the Cataract formation represented in the Silurian section of this region.

LOWER PALEOZOIC ROCKS OF THE SOUTHERN NEW MEXICO REGION

BY N. H. DARTON

(*Abstract*)

In studying various mountain uplifts in southern New Mexico many new data have been obtained as to the distribution and relations of the representatives of parts of Cambrian, Ordovician, Silurian, Devonian, and Mississippian times. These rocks thin to the north and disappear near latitude 34°, beyond which the Pennsylvanian formations lie on pre-Cambrian granite and schist. The overlap relations of the rocks of the various systems are somewhat complex, and it has not been possible to ascertain to what extent the absence of certain formations is due to non-deposition or to removal by erosion. It was found that the Bliss sandstone, El Paso, Montoya, and Fusselman limestones, Percha shale, and Mississippian limestone are well represented in the San Andreas Mountains, most of them extending to its north end. They are also exposed in the great section in the west slope of the Sacramento Mountains southeast of Alamagordo. The El Paso, Montoya, and Fusselman limestones are prominent in the Lake Valley, Caballos and Cooks Range uplifts, as well as in some of the ranges in Luna County. The formations are remarkably constant in their characteristics and yield many distinctive fossils.

To be published as Part C, Professional Paper 108, United States Geological Survey.

Presented by title in the absence of the author.

LOCKPORT-GUELPH SECTION IN THE BARGE CANAL AT ROCHESTER, NEW YORK

BY GEORGE HALCOTT CHADWICK

(*Abstract*)

The deep cut for the barge canal through the Niagara escarpment just west of Rochester affords temporarily a continuous section of the Lockport and Guelph dolomites from base to practical summit, the first such section ever available. This is being studied layer by layer, as it will become permanently under water when the cut is completed. The sections now accessible include 90 feet of Guelph strata from the summit down, reaching 6 feet down into the Eramosa beds of Williams, and 60 feet of Lockport above the Decew member (10 feet), with a gap of possibly 15 feet not yet excavated in the Eramosa beds of Williams. The positions of the two Shelby horizons have been determined and shown to belong within the limits assigned to them hypothetically by Williams.

This paper will be published in the Proceedings of the Rochester Academy of Sciences.

Presented in abstract extemporaneously.

Discussion

Mr. M. Y. **Williams**: The section along the barge canal at Rochester is, in my opinion, the finest Lockport-Guelph section in eastern North America. The thin, bituminous, Eramosa beds, described by Dr. William Logan as forming the top of the Niagara (Lockport) formation at Guelph, have been shown by Professor Chadwick to occupy a similar position at Rochester. The Lower Shelby horizon at the base of the Eramosa beds at the Niagara Falls, as determined by Clarke and Ruedemann, corresponds with the horizon of a fauna found by me at Guelph which contains Guelph species mixed with Lockport species. The Upper Shelby fauna is in the true Guelph.

Miss M. **O'Connell**: I have two questions to put to the writer of this paper. The first is: Has he determined the origin of the carbonaceous material in the Eramosa beds? The second is: What is the fauna of the beds? Have the same eurypterids been found as Mr. Williams discovered in the Eramosa beds of Ontario?

Author's reply to Miss O'Connell: The dolomites above the true Lockport at Rochester are all bituminous. The origin of the bitumen is probably not different from that in the Onondaga, Falkirk, and other marine limestones. Collecting in the Eramosa beds waits on the excavation. Eurypterid fragments have, however, been obtained in the Upper Rochester (Homalonotus beds) at Rochester.

CAYUGAN WATERLIMES OF WESTERN NEW YORK

BY GEORGE HALCOTT CHADWICK

(*Abstract*)

Restudy and careful measurement of the uppermost Silurian (Ontaric) sections along the Onondaga escarpment from Bertie, Ontario, to the meridian of Rochester, New York, show the following well characterized subdivisions, with their approximate thicknesses:

Akron dolomite (Grabau), subcrystalline, gray to brownish, with *Cyathophyllum hydraulicum*	12 feet or less
Buffalo cement bed, carrying eurypterids	6 feet
Scajaquada dark shales and blocky waterlimes At base the Bridgeburg horizon, with eurypterids.	8 feet
Falkirk dolomite, brownish and bituminous, below massive and often producing waterfalls Carries a marine fauna, but eurypterids at base.	30 feet
Oatka beds, dark gray and shaly, with a blocky waterlime at base carrying eurypterids	20 feet or less

These rest with an irregular, apparently disconformable, contact on the ashen, pitted shales of the Camillus gypsite series at all localities where the exposures go so low.

The upper three members are found to be discontinuous across western New York through pre-Onondaga erosion, and in their absence the Falkirk has been partly or wholly referred to the Cobleskill. But they come in again at fairly regular intervals of about 30 miles each along the outcrop, thus indicating a series of gentle swells in the Silurian strata which have been truncated in the Onondaga transgression.

It is claimed that the name Bertie should either be retained in the primitive sense, covering the entire series inclusive of the Akron, or else be restricted to the cement bed here called the Buffalo, a name said to be preoccupied. The correlation eastward of the Akron with the Cobleskill remains to be worked out anew, but it is now believed to be substantially correct.

Presented in full extemporaneously.

Brief remarks were made by Prof. A. W. Grabau and Miss M. O'Connell; also by Mr. M. Y. Williams, who said:

I wish to make a plea for the continued use of the term Bertie. At the type locality it was clearly used to include the beds below the Akron dolomite and above the Camillus shale, although the shale is not exposed. I see no difficulty, therefore, in continuing its use as above, which is the usage adopted by Professor Grabau in Bulletin 45, New York State Museum.

SUMMARY OF GEOLOGICAL INVESTIGATIONS CONNECTED WITH THE CATSKILL AQUEDUCT

BY CHARLES P. BERKEY

(*Abstract*)

The work of construction of the Catskill Aqueduct, so far as it relates to geological investigations and discoveries, is practically completed. The only portion which is likely to add data is the newly projected Schoharie supply. Even here preliminary investigations are almost completed; but the construction of the Gilboa Dam and the eighteen-mile tunnel projected through the Catskill Mountains from the Schoharie to the Esopus watershed is not yet begun.

All of the work from Ashokan reservoir to and through New York City, however, has been completed; and it is now possible to compare the geological interpretations given during the time of exploratory investigation with the actual results proven under construction. The New York City Board of Water Supply has assigned the writer to the task of preparing a summary of the geological findings. It is proposed to write a final volume covering this special field, with an attempt to show the intimate connection between the geological findings and the modification of plan and ultimate success of the different parts of the enterprise.

This piece of work is one of the most prominent in the history of large engineering enterprises for the close cooperation of engineers and geologists, and it is one in which the variety of problems is great enough to make it useful as an illustration of the interdependence of geology and engineering.

The brief discussion given was confined to a few typical illustrations of this close relation between the plans of the engineering work and the conditions interpreted from the geology.

Presented in abstract extemporaneously.

At 4.55 o'clock the reading of the scientific papers offered at the Twenty-ninth Annual Meeting of the Geological Society of America was concluded.

VOTE OF THANKS

In appreciation of the excellent work of the local committee in arranging for this meeting and of the Department of Education of the State of New York in furnishing accommodations, the following resolution was adopted:

> *Resolved*, That the Geological and Paleontological Societies of America extend to the local committee, and to the geological department of the State Museum and others who assisted them, their most sincere thanks for the excellent and charming arrangements made for the reception and entertainment of the societies during the very pleasant and profitable meetings now drawing to a close.

The Society adjourned at 5 o'clock.

Register of the Albany Meeting, 1916

FELLOWS

Frank D. Adams
Wallace W. Atwood
Joseph A. Bancroft
Joseph Barrell
R. S. Bassler
Charles P. Berkey
Edward W. Berry
Eliot Blackwelder
J. A. Bownocker
E. B. Branson
Alfred H. Brooks
Charles W. Brown
Charles Butts
D. D. Cairnes
George H. Chadwick
Rollin T. Chamberlin
Frederick G. Clapp
John M. Clarke
H. F. Cleland
A. P. Coleman
Alja R. Crook
Henry P. Cushing
Arthur L. Day
Reginald A. Daly
John A. Dresser
B. K. Emerson
C. N. Fenner
August F. Foerste
M. L. Fuller
James H. Gardner
L. C. Glenn
James W. Goldthwait
C. E. Gordon
Charles N. Gould
Amadeus W. Grabau
Walter Granger
L. C. Graton
Herbert E. Gregory
Arnold Hague
C. A. Hartnagel

Thomas C. Hopkins
W. O. Hotchkiss
Erasmus Haworth
George D. Hubbard
E. C. Jeffrey
Douglas W. Johnson
George F. Kay
Arthur Keith
E. M. Kindle
Cyril W. Knight
Edward H. Kraus
Henry B. Kümmel
Alfred C. Lane
Charles K. Leith
A. G. Leonard
Frank Leverett
Waldemar Lindgren
Frederic B. Loomis
Richard S. Lull
S. W. McCallie
Lawrence Martin
Edward B. Mathews
W. D. Matthew
J. C. Merriam
Willett G. Miller
William John Miller
Fred H. Moffit
David H. Newland
Ida H. Ogilvie
Henry Fairfield Osborn
Sidney Paige
W. C. Phalen
A. H. Phillips
Joseph Hyde Pratt
A. H. Purdue
Chester A. Reeds
Harry Fielding Reid
William North Rice
John L. Rich
Heinrich Ries
Rudolf Ruedemann
T. E. Savage
Charles Schuchert
E. H. Sellards
Eugene Wesley Shaw
Burnett Smith
George Otis Smith
Philip S. Smith
J. Stanley-Brown
Frank B. Taylor
W. H. Twenhofel
M. W. Twitchell
J. B. Tyrrell
E. O. Ulrich
Frank R. Van Horn
Gilbert Van Ingen
T. Wayland Vaughan
T. L. Walker
Thomas L. Watson
Lewis G. Westgate
Edgar T. Wherry
David White
G. R. Wieland
J. B. Woodworth
G. Frederick Wright

FELLOWS-ELECT

Marcus I. Goldman
Edward Steidtmann

In addition to the foregoing, there were registered at the meeting 18 members of the Paleontological Society and 68 visitors.

OFFICERS, CORRESPONDENTS, AND FELLOWS OF THE GEOLOGICAL SOCIETY OF AMERICA

OFFICERS FOR 1917

President:

Frank D. Adams, Montreal, Canada

Vice-Presidents:

Andrew C. Lawson, Berkeley, Cal.
W. D. Matthew, New York, N. Y.
J. C. Merriam, Berkeley, Cal.

Secretary:

Edmund Otis Hovey, American Museum of Natural History,
New York, N. Y.

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Editor:

J. Stanley-Brown, 26 Exchange Place, New York, N. Y.

Librarian:

F. R. Van Horn, Cleveland, Ohio

Councilors:

(Term expires 1917)

Charles K. Leith, Madison, Wis.
Thomas L. Watson, Charlottesville, Va.

(Term expires 1918)

Frank B. Taylor, Fort Wayne, Ind.
Charles P. Berkey, New York, N. Y.

(Term expires 1919)

Arthur L. Day, Washington, D. C.
William H. Emmons, Minneapolis, Minn.

MEMBERSHIP, 1917

CORRESPONDENTS

Charles Barrois, Lille; France. December, 1909.
W. C. Brögger, Christiania, Norway. December, 1909.
Giovanni Capellini, Bologna, Italy. December, 1910.
Baron Gerhard De Geer, Stockholm, Sweden. December, 1910.
Sir Archibald Geikie, Hasslemere, England. December, 1909.
Albert Heim, Zürich, Switzerland. December, 1909.
Emanuel Kayser, Marburg, Germany. December, 1909.
W. Kilian, Grenoble, France. December, 1912.
J. J. H. Teall, London, England. December, 1912.
Emil Tietze, Vienna, Austria. December, 1910.

FELLOWS

*Indicates Original Fellow (see article III of Constitution)

Cleveland Abbe, Jr., U. S. Weather Bureau, Washington, D. C. August, 1899.
Frank Dawson Adams, McGill University, Montreal, Canada. Dec., 1889.
George I. Adams, 17 San T'iao Hutung, Peking, China. December, 1902.
José Guadalupe Aguilera, Instituto Geologico, Mexico, Mexico. Aug., 1896.
William Clinton Alden, U. S. Geological Survey, Washington, D. C. December, 1909.
Truman H. Aldrich, Birmingham, Ala. May, 1889.
John A. Allan, University of Alberta, Strathcona, Canada. December, 1914.
R. C. Allen, State Geological Survey, Lansing, Mich. December, 1911.
Henry M. Ami, Strathcona Park, Ottawa, Canada. December, 1889.
Frank M. Anderson, State Mining Bureau, 2604 Ætna St., Berkeley, Cal. June, 1902.
Robert Van Vleck Anderson, 7 Richmond Terrace, Whitehall, S. W., London, England. December, 1911.
Ralph Arnold, 923 Union Oil Building, Los Angeles, Cal. December, 1904.
George Hall Ashley, U. S. Geological Survey, Washington, D. C. Aug., 1895.
Wallace Walter Atwood, Harvard University, Cambridge, Mass. Dec., 1909.
Rufus Mather Bagg, Jr., 7 Brokaw Place, Appleton, Wis. December, 1896.
Harry Foster Bain, 734 Salisbury House, London, E. C., England. Dec., 1895.
Manley Benson Baker, School of Mining, Kingston, Ontario. Dec., 1911.
S. Prentiss Baldwin, 2930 Prospect Ave., Cleveland, Ohio. August, 1895.
Sydney H. Ball, 71 Broadway, New York City. December, 1905.
Joseph A. Bancroft, McGill University, Montreal, Canada. December, 1914.
Erwin Hinckley Barbour, University of Nebraska, Lincoln, Neb. Dec., 1896.
Joseph Barrell, Yale University, New Haven, Conn. December, 1902.
George H. Barton, Boston Society of Natural History, Boston, Mass. August, 1890.
Florence Bascom, Bryn Mawr College, Bryn Mawr, Pa. August, 1894.
Ray Smith Bassler, U. S. National Museum, Washington, D. C. Dec., 1906.
Edson Sunderland Bastin, U. S. Geological Survey, Washington, D. C. December, 1909.
Alan Mara Bateman, Yale University, New Haven, Conn. December, 1916.

William S. Bayley, University of Illinois, Urbana, Ill. December, 1888.
*George F. Becker, U. S. Geological Survey, Washington, D. C.
Joshua W. Beede, Indiana University, Bloomington, Ind. December, 1902.
Robert Bell, Geological Survey, Department of Mines, Ottawa, Canada. May, 1889.
Charles P. Berkey, Columbia University, New York, N. Y. August, 1901.
Edward Wilber Berry, Johns Hopkins University, Baltimore, Md. Dec., 1909.
Samuel Walker Beyer, Iowa Agricultural College, Ames, Iowa. Dec., 1896.
Eliot Blackwelder, University of Illinois, Urbana, Ill. December, 1908.
John M. Boutwell, 1323 De la Vine St., Santa Barbara, Cal. Dec., 1905.
Charles F. Bowen, U. S. Geological Survey, Washington, D. C. Dec., 1916.
John Adams Bownocker, Ohio State University, Columbus, Ohio. Dec., 1904.
*John C. Branner, Leland Stanford, Jr., University, Stanford University, Cal.
Edwin Bayer Branson, University of Missouri, Columbia, Mo. Dec., 1911.
Albert Perry Brigham, Colgate University, Hamilton, N. Y. December, 1893.
Reginald W. Brock, University of British Columbia, Vancouver, B. C. December, 1904.
Alfred Hulse Brooks, U. S. Geological Survey, Washington, D. C. Aug., 1899.
Amos P. Brown, University of Pennsylvania, Philadelphia, Pa. Dec., 1905.
Barnum Brown, American Museum of Natural History, New York, N. Y. December, 1910.
Charles Wilson Brown, Brown University, Providence, R. I. Dec., 1908.
Thomas Clachar Brown, Bryn Mawr College, Bryn Mawr, Pa. Dec., 1915.
Henry Andrew Buehler, Rolla, Mo. December, 1909.
Edward Moore Jackson Burwash, University of Toronto, Toronto, Canada. December, 1916.
Bert S. Butler, U. S. Geological Survey, Washington, D. C. December, 1912.
G. Montague Butler, College of Mines, Tucson, Arizona. December, 1911.
Charles Butts, U. S. Geological Survey, Washington, D. C. December, 1912.
De Lorme Donaldson Cairnes, Geological Survey Branch, Department of Mines, Ottawa, Canada. December, 1912.
Fred Harvey Hall Calhoun, Clemson College, S. C. December, 1909.
Frank C. Calkin, U. S. Geological Survey, Washington, D. C. Dec., 1914.
Henry Donald Campbell, Washington and Lee University, Lexington, Va. May, 1889.
Marius R. Campbell, U. S. Geological Survey, Washington, D. C. Aug., 1892.
Charles Camsell, Geological Survey of Canada, Ottawa, Canada. December, 1914.
Stephen R. Capps, Jr., U. S. Geological Survey, Washington, D. C. Dec., 1911.
Frank Carney, Granville, Ohio. December, 1908.
Ermine C. Case, University of Michigan, Ann Arbor, Mich. December, 1901.
George H. Chadwick, University of Rochester, Rochester, N. Y. Dec., 1911.
Rollin T. Chamberlin, University of Chicago, Chicago, Ill. December, 1913.
*T. C. Chamberlin, University of Chicago, Chicago, Ill.
Clarence Raymond Claghorn, Tacoma, Wash. August, 1891.
Charles H. Clapp, University of Arizona, Tucson, Arizona. December, 1914.
Frederick G. Clapp, 120 Broadway, New York, N. Y. December, 1905.
*William Bullock Clark, Johns Hopkins University, Baltimore, Md.
John Mason Clarke, Albany, N. Y. December, 1897.
Herdman F. Cleland, Williams College, Williamstown, Mass. Dec., 1905.

J. MORGAN CLEMENTS, 20 Broad St., New York City. December, 1894.
COLLIER COBB, University of North Carolina, Chapel Hill, N. C. Dec., 1894.
ARTHUR P. COLEMAN, Toronto University, Toronto, Canada. December, 1896.
GEORGE L. COLLIE, Beloit College, Beloit, Wis. December, 1897.
ARTHUR J. COLLIER, U. S. Geological Survey, Washington, D. C. June, 1902.
D. DALE CONDIT, U. S. Geological Survey, Washington, D. C. December, 1916.
CHARLES W. COOK, University of Michigan, Ann Arbor, Mich. Dec., 1915.
EUGENE COSTE, 1943 11th St., West, Calgary, Alberta, Canada. Dec., 1906.
RALPH DIXON CRAWFORD, University of Colorado, Boulder, Colo. Dec., 1916.
ALJA ROBINSON CROOK, State Museum of Natural History, Springfield, Ill. December, 1898.
*WILLIAM O. CROSBY, Massachusetts Institute of Technology, Boston, Mass.
WHITMAN CROSS, U. S. Geological Survey, Washington, D. C. May, 1889.
GARRY E. CULVER, 1104 Wisconsin St., Stevens Point, Wis. December, 1891.
EDGAR R. CUMINGS, Indiana University, Bloomington, Ind. August, 1901.
*HENRY P. CUSHING, Western Reserve University, Cleveland, Ohio..
REGINALD A. DALY, Harvard University, Cambridge, Mass. December, 1905.
EDWARD SALISBURY DANA, Yale University, New Haven, Conn. Dec., 1908.
*NELSON H. DARTON, U. S. Geological Survey, Washington, D. C.
*WILLIAM M. DAVIS, Harvard University, Cambridge, Mass.
ARTHUR LOUIS DAY, Geophysical Laboratory, Carnegie Institution, Washington, D. C. December, 1909.
DAVID T. DAY, 1333 F St. N. W., Washington, D. C. August, 1891.
BASHFORD DEAN, Columbia University, New York, N. Y. December, 1910.
ALEXANDER DEUSSEN, University of Texas, Austin, Texas. December, 1916.
FRANK WILBRIDGE DE WOLF, Urbana, Ill. December, 1909.
*JOSEPH S. DILLER, U. S. Geological Survey, Washington, D. C.
EDWARD V. D'INVILLIERS, 518 Walnut St., Philadelphia, Pa. December, 1888.
RICHARD E. DODGE, Dodge Farm, Washington, Conn. August, 1897.
NOAH FIELDS DRAKE, Fayetteville, Arkansas. December, 1898.
JOHN ALEXANDER DRESSER, 326 Notre Dame de Grace Ave., Montreal, Canada. December, 1906.
CHARLES R. DRYER, Oak Knoll, Fort Wayne, Ind. August, 1897.
CHARLES WALES DRYSDALE, Geological Survey, Ottawa, Canada. Dec., 1916.
*EDWIN T. DUMBLE, 2003 Main St., Houston, Texas.
ARTHUR S. EAKLE, University of California, Berkeley, Cal. December, 1899.
CHARLES R. EASTMAN, American Museum of Natural History, New York, N. Y. December, 1895.
EDWIN C. ECKEL, Munsey Building, Washington, D. C. December, 1905.
*BENJAMIN K. EMERSON, Amherst College, Amherst, Mass.
WILLIAM HARVEY EMMONS, University of Minnesota, Minneapolis, Minn. December, 1912.
JOHN EYERMAN, Oakhurst, Easton, Pa. August, 1891.
HAROLD W. FAIRBANKS, Berkeley, Cal. August, 1892.
*HERMAN L. FAIRCHILD, University of Rochester, Rochester, N. Y.
OLIVER C. FARRINGTON, Field Museum of Natural History, Chicago, Ill. December, 1895.
NEVIN M. FENNEMAN, University of Cincinnati, Cincinnati, Ohio. Dec., 1904.
CLARENCE NORMAN FENNER, Geophysical Laboratory, Washington, D. C. December, 1911.

Cassius Asa Fisher, 711 Ideal Building, Denver, Colo. December, 1908.
August F. Foerste, 128 Rockwood Ave., Dayton, Ohio. December, 1899.
William Ebenezer Ford, Sheffield Scientific School, New Haven, Conn. December, 1915.
Myron Leslie Fuller, 131 State St., Boston, Mass. December, 1898.
Henry Stewart Gane, Wonalancet, New Hampshire. December, 1896.
James H. Gardner, 510 New Daniel Bldg., Tulsa, Oklahoma. December, 1911.
Russell D. George, University of Colorado, Boulder, Colo. December, 1906.
*Grove K. Gilbert, U. S. Geological Survey, Washington, D. C.
Adam Capen Gill, Cornell University, Ithaca, N. Y. December, 1888.
L. C. Glenn, Vanderbilt University, Nashville, Tenn. June, 1900.
Marcus Isaac Goldman, U. S. Geological Survey, Washington, D. C. Dec., 1916.
James Walter Goldthwait, Dartmouth College, Hanover, N. H. Dec., 1909.
Charles H. Gordon, University Library, University of Tennessee, Knoxville, Tenn. August, 1893.
Clarence E. Gordon, Massachusetts Agricultural College, Amherst, Mass. December, 1913.
Charles Newton Gould, 1218 Colcord Bldg., Oklahoma City, Okla. December, 1904.
Amadeus W. Grabau, Columbia University, New York, N. Y. December, 1898.
Walter Granger, American Museum of Natural History, New York, N. Y. December, 1911.
Ulysses Sherman Grant, Northwestern University, Evanston, Ill. Dec., 1890.
John Sharshall Grasty, University of Virginia, University, Va. Dec., 1911.
Louis C. Graton, Harvard University, Cambridge, Mass. December, 1913.
Herbert E. Gregory, Yale University, New Haven, Conn. August, 1901.
George P. Grimsley, 31st and Calvert Sts., Gilman 3-B, Baltimore, Md. August, 1895.
Leon S. Griswold, Plymouth, Mass. August, 1902.
Frederic P. Gulliver, 1112 Morris Bldg., Philadelphia, Pa. August, 1895.
William F. E. R. Gurley, University of Chicago, Chicago, Ill. Dec., 1914.
Arnold Hague, U. S. Geological Survey, Washington, D. C. May, 1889.
Baird Halberstadt, Pottsville, Pa. December, 1909.
Gilbert D. Harris, Cornell University, Ithaca, N. Y. December, 1903.
John Burchmore Harrison, Georgetown, British Guiana. June, 1902.
Chris. A. Hartnagel, Education Building, Albany, N. Y. December, 1913.
John B. Hastings, 1480 High St., Denver, Colo. May, 1889.
*Erasmus Haworth, University of Kansas, Lawrence, Kans.
Ray Vernon Hennen, West Virginia Geological Survey, Morgantown, W. Va. December, 1914.
Oscar H. Hershey, Kellogg, Idaho. December, 1909.
Donnel Foster Hewett, U. S. Geological Survey, Washington, D. C. Dec., 1916.
Richard R. Hice, Beaver, Pa. December, 1903.
*Robert T. Hill, Federal Bldg., Los Angeles, Cal.
Richard C. Hills, Denver, Colo. August, 1894.
Henry Hinds, U. S. Geological Survey, Washington, D. C. December, 1912.
*Charles H. Hitchcock, 2376 Oahu Ave., Honolulu, Hawaiian Islands.
William H. Hobbs, University of Michigan, Ann Arbor, Mich. Aug., 1891.
*Levi Holbrook, P. O. Box 536, New York, N. Y.
Roy J. Holden, Virginia Polytechnic Institute, Blacksburg, Va. Dec., 1914.

William Jacob Holland, Carnegie Museum, Pittsburgh, Pa. December, 1910.

Arthur Hollick, Staten Island Association of Arts and Sciences, New Brighton, S. I. August, 1898.

Thomas C. Hopkins, Syracuse University, Syracuse, N. Y. December, 1894.

William Otis Hotchkiss, State Geological Survey, Madison, Wis. Dec., 1911.

*Edmund Otis Hovey, American Museum of Natural History, New York, N. Y.

Ernest Howe, 77 Rhode Island Ave., Newport, R. I. December, 1903.

George D. Hubbard, Oberlin College, Oberlin, Ohio. December, 1914.

Lucius L. Hubbard, Houghton, Mich. December, 1894.

Walter F. Hunt, University of Michigan, Ann Arbor, Mich. December, 1914.

Ellsworth Huntington, 222 Highland St., Milton, Mass. December, 1906.

Louis Hussakof, American Museum of Natural History, New York, N. Y. December, 1910.

Joseph P. Iddings, Brinklow, Md. May, 1889.

John D. Irving, Yale University, New Haven, Conn. December, 1905.

A. Wendell Jackson, 9 Desbrosses St., New York, N. Y. December, 1888.

Robert T. Jackson, 195 Bay State Road, Boston, Mass. August, 1894.

Thomas Augustus Jaggar, Jr., Hawaiian Volcano Observatory, Territory of Hawaii, U. S. A. December, 1906.

Mark S. W. Jefferson, Michigan State Normal College, Ypsilanti, Mich. December, 1904.

Edward C. Jeffrey, Harvard University, Cambridge, Mass. December, 1914.

Albert Johannsen, University of Chicago, Chicago, Ill. December, 1908.

Douglas Wilson Johnson, Columbia University, New York, N. Y. Dec., 1906.

William Alfred Johnston, Geological Survey, Ottawa, Canada. Dec., 1916.

Alexis A. Julien, South Harwich, Mass. May, 1889.

Frank James Katz, U. S. Geological Survey, Washington, D. C. Dec., 1912.

George Frederick Kay, State University of Iowa, Iowa City, Iowa. Dec., 1908.

Arthur Keith, U. S. Geological Survey, Washington, D. C. May, 1889.

*James F. Kemp, Columbia University, New York, N. Y.

Charles Rollin Keyes, 944 Fifth St., Des Moines, Iowa. August, 1890.

Edward M. Kindle, Victoria Memorial Museum, Ottawa, Canada. Dec., 1905.

Charles Townsend Kirk, University of New Mexico, Albuquerque, New Mexico. December, 1915.

Edwin Kirk, U. S. Geological Survey, Washington, D. C. December, 1912.

Cyril Workman Knight, Toronto, Ontario, Canada. December, 1911.

Adolph Knopf, U. S. Geological Survey, Washington, D. C. December, 1911.

Frank H. Knowlton, U. S. National Museum, Washington, D. C. May, 1889.

Edward Henry Kraus, University of Michigan, Ann Arbor, Mich. June, 1902.

Henry B. Kümmel, Trenton, N. J. December, 1895.

*George F. Kunz, 401 Fifth Ave., New York, N. Y.

George Edgar Ladd, State College, N. M. August, 1891.

Lawrence Morris Lambe, Department of Mines, Ottawa, Canada. Dec., 1911.

Henry Landes, University of Washington, University Station, Seattle, Wash. December, 1908.

Alfred C. Lane, Tufts College, Mass. December, 1889.

Esper S. Larsen, Jr., U. S. Geological Survey, Washington, D. C. Dec., 1914.

Andrew C. Lawson, University of California, Berkeley, Cal. May, 1889.

Willis Thomas Lee, U. S. Geological Survey, Washington, D. C. Dec., 1903.

James H. Lees, Iowa Geological Survey, Des Moines, Iowa. December, 1914.

Charles K. Leith, University of Wisconsin, Madison, Wis. Dec., 1902.

Arthur G. Leonard, State University of North Dakota, Grand Forks, N. Dak. December, 1901.

Frank Leverett, Ann Arbor, Mich. August, 1890.

Joseph Volney Lewis, Rutgers College, New Brunswick, N. J. Dec., 1906.

William Libbey, Princeton University, Princeton, N. J. August, 1899.

Waldemar Lindgren, Massachusetts Institute of Technology, Boston, Mass. August, 1890.

Miguel A. R. Lisboa, Irrigation and Water Supply Service, Rio de Janeiro, Brazil. December, 1913.

Frederick Brewster Loomis, Amherst College, Amherst, Mass. Dec., 1909.

George Davis Louderback, University of California, Berkeley, Cal. June, 1902.

Gerald Francis Loughlin, U. S. Geological Survey, Washington, D. C. December, 1916.

Robert H. Loughridge, University of California, Berkeley, Cal. May, 1889.

Albert P. Low, Department of Mines, Ottawa, Canada. December, 1905.

Richard Swann Lull, Yale University, New Haven, Conn. December, 1909.

Charles T. Lupton, Cosden Oil and Gas Company, Tulsa, Okla. Dec., 1916.

Samuel Washington McCallie, Atlanta, Ga. December, 1909.

Hiram Deyer McCaskey, U. S. Geological Survey, Washington, D. C. December, 1904.

Richard G. McConnell, Geological and Natural History Survey of Canada, Ottawa, Canada. May, 1889.

Donald Francis MacDonald, U. S. Geological Survey, Washington, D. C. December, 1915.

James Rieman Macfarlane, Woodland Road, Pittsburgh, Pa. August, 1891.

William McInnes, Geological and Natural History Survey of Canada, Ottawa, Canada. May, 1889.

Peter McKellar, Fort William, Ontario, Canada. August, 1890.

George Rogers Mansfield, 2067 Park Road N. W., Washington, D. C. December, 1909.

Curtis F. Marbut, Bureau of Soils, Washington, D. C. August, 1897.

Vernon F. Marsters, Rushville, Ind. August, 1892.

George Curtis Martin, U. S. Geological Survey, Washington, D. C. June, 1902.

Lawrence Martin, University of Wisconsin, Madison, Wis. December, 1909.

Edward B. Mathews, Johns Hopkins University, Baltimore, Md. Aug., 1895.

Francois E. Matthes, U. S. Geological Survey, Washington, D. C. December, 1914.

W. D. Matthew, American Museum of Natural History, New York, N. Y. December, 1903.

Thomas Poole Maynard, 1622 D. Hurt Bldg., Atlanta, Ga. December, 1914.

Warren Judson Mead, University of Wisconsin, Madison, Wis. Dec., 1916.

Oscar E. Meinzer, U. S. Geological Survey, Washington, D. C. December, 1916.

P. H. Mell, 165 East 10th St., Atlanta, Ga. December, 1888.

Walter C. Mendenhall, U. S. Geological Survey, Washington, D. C. June, 1902.

John C. Merriam, University of California, Berkeley, Cal. August, 1895.

George P. Merrill, U. S. National Museum, Washington, D. C. Dec., 1888.

Herbert E. Merwin, Geophysical Laboratory, Washington, D. C. Dec., 1914.

Arthur M. Miller, State University of Kentucky, Lexington, Ky. Dec., 1897.
Benjamin L. Miller, Lehigh University, South Bethlehem, Pa. Dec., 1904.
Willet G. Miller, Toronto, Canada. December, 1902.
William John Miller, Smith College, Northampton, Mass. December, 1909.
Hugh D. Miser, U. S. Geological Survey, Washington, D. C. December, 1916.
Fred Howard Moffit, U. S. Geological Survey, Washington, D. C. Dec., 1912.
G. A. F. Molengraaf, Technical High School, Delft, Holland. December, 1913.
Henry Montgomery, University of Toronto, Toronto, Canada. Dec., 1904.
Elwood S. Moore, Pennsylvania State College, State College, Pa. Dec., 1911.
Malcolm John Munn, Clinton Bldg., Tulsa, Okla. December, 1909.
*Frank L. Nason, West Haven, Conn.
David Hale Newland, Albany, N. Y. December, 1906.
John F. Newsom, Leland Stanford, Jr., University, Stanford University, Cal. December, 1899.
Levi F. Noble, Valyermo, Cal. December, 1916.
William H. Norton, Cornell College, Mount Vernon, Iowa. December, 1895.
Charles J. Norwood, State University, Lexington, Ky. August, 1894.
Ida Helen Ogilvie, Barnard College, Columbia University, New York, N. Y. December, 1906.
Cleophas C. O'Harra, South Dakota School of Mines, Rapid City, S. Dak. December, 1904.
Daniel Webster Ohern, University of Oklahoma, Norman, Okla. Dec., 1911.
Ezequiel Ordonez, 2 a General Prim 43, Mexico, D. F., Mex. August, 1896.
Edward Orton, Jr., Columbus, Ohio. December, 1909.
Henry F. Osborn, American Museum of Natural History, New York, N. Y. August, 1894.
Robert W. Pack, U. S. Geological Survey, Washington, D. C. December, 1916.
Sidney Paige, U. S. Geological Survey, Washington, D. C. December, 1911.
Charles Palache, Harvard University, Cambridge, Mass. August, 1897.
William A. Parks, University of Toronto, Toronto, Canada. December, 1906.
*Horace B. Patton, Colorado School of Mines, Golden, Colo.
Frederick B. Peck, Lafayette College, Easton, Pa. August, 1901.
Richard A. F. Penrose, Jr., 460 Bullitt Bldg., Philadelphia, Pa. May, 1889.
George H. Perkins, University of Vermont, Burlington, Vt. June, 1902.
Joseph H. Perry, 276 Highland St., Worcester, Mass. December, 1888.
Olaf August Peterson, Carnegie Museum, Pittsburgh, Pa. December, 1910.
William C. Phalen, U. S. Bureau of Mines, Washington, D. C. Dec., 1912.
Alexander H. Phillips, Princeton University, Princeton, N. J. Dec., 1914.
Louis V. Pirsson, Yale University, New Haven, Conn. August, 1894.
Joseph E. Pogue, Northwestern University, Evanston, Ill. December, 1911.
Joseph Hyde Pratt, North Carolina Geological Survey, Chapel Hill, N. C. December, 1898.
William Armstrong Price, Jr., West Virginia University, Morgantown, W.Va. December, 1916.
Louis M. Prindle, U. S. Geological Survey, Washington, D. C. Dec., 1912.
William Frederick Prouty, University of Alabama, University, Ala. December, 1911.
*Raphael Pumpelly, Newport, R. I.
Albert Homer Purdue, State Geological Survey, Nashville, Tenn. Dec., 1904.

FREDERICK LESLIE RANSOME, U. S. Geological Survey, Washington, D. C. August, 1895.

PERCY EDWARD RAYMOND, Museum of Comparative Zoölogy, Cambridge, Mass December, 1907.

CHESTER A. REEDS, American Museum of Natural History, New York, N. Y. December, 1913.

HARRY FIELDING REID, Johns Hopkins University, Baltimore, Md. Dec., 1892.

LEOPOLD REINECKE, Geological Survey, Ottawa, Canada. December, 1916.

WILLIAM NORTH RICE, Wesleyan University, Middletown, Conn. August, 1890.

JOHN LYON RICH, University of Illinois, Urbana, Ill. December, 1912.

CHARLES H. RICHARDSON, Syracuse University, Syracuse, N. Y. Dec., 1899.

GEORGE BURR RICHARDSON, U. S. Geological Survey, Washington, D. C. December, 1908.

HEINRICH RIES, Cornell University, Ithaca, N. Y. December, 1893.

ELMER S. RIGGS, Field Museum of Natural History, Chicago, Ill. Dec., 1911.

HENRY HOLLISTER ROBINSON, Peabody Museum, New Haven, Conn. Dec., 1916.

BRUCE ROSE, Geological Survey, Ottawa, Canada. December, 1916.

JESSE PERRY ROWE, University of Montana, Missoula, Mont. December, 1911.

RUDOLF RUEDEMANN, Albany, N. Y. December, 1905.

JOHN JOSEPH RUTLEDGE, Experiment Station, Pittsburgh, Pa. Dec., 1911.

ORESTES H. ST. JOHN, 1141 Twelfth St., San Diego, Cal. May, 1889.

RENO H. SALES, Anaconda Copper Mining Company, Butte, Mon. Dec., 1916.

*ROLLIN D. SALISBURY, University of Chicago, Chicago, Ill.

FREDERICK W. SARDESON, University of Minnesota, Minneapolis, Minn. December, 1892.

THOMAS EDMUND SAVAGE, University of Illinois, Urbana, Ill. December, 1907.

FRANK C. SCHRADER, U. S. Geological Survey, Washington, D. C. Aug., 1901.

CHARLES SCHUCHERT, Yale University, New Haven, Conn. August, 1895.

ALFRED REGINALD SCHULTZ, U. S. Geological Survey, Washington, D. C. December, 1912.

WILLIAM B. SCOTT, Princeton University, Princeton, N. J. August, 1892.

ARTHUR EDMUND SEAMAN, Michigan College of Mines, Houghton, Mich. December, 1904.

HENRY M. SEELY, Middlebury College, Middlebury, Vt. May, 1889.

ELIAS H. SELLARDS, Tallahassee, Fla. December, 1905.

JOAQUIM CANDIDO DA COSTA SEÑA, State School of Mines, Ouro Preto, Brazil. December, 1908.

MILLARD K. SHALER, 4 Bishopsgate E. C., London, England. December, 1914.

GEORGE BURBANK SHATTUCK, Vassar College, Poughkeepsie, N. Y. Aug., 1899.

EUGENE WESLEY SHAW, U. S. Geological Survey, Washington, D. C. Dec., 1912.

SOLON SHEDD, State College of Washington, Pullman, Wash. Dec., 1904.

EDWARD M. SHEPARD, 1403 Benton Ave., Springfield, Mo. August, 1901.

BOHUMIL SHIMEK, University of Iowa, Iowa City, Iowa. December, 1904.

HERVEY WOODBURN SHIMER, Massachusetts Institute of Technology, Boston, Mass. December, 1910.

CLAUDE ELLSWORTH SIEBENTHAL, U. S. Geological Survey, Washington, D. C. December, 1912.

*FREDERICK W. SIMONDS, University of Texas, Austin, Texas.

WILLIAM JOHN SINCLAIR, Princeton University, Princeton, N. J. Dec., 1906.

Joseph Theophilus Singewald, Johns Hopkins University, Baltimore, Md. December, 1911.

Earle Sloan, Charleston, S. C. December, 1908.

Burnett Smith, Syracuse University, Skaneateles, N. Y. December, 1911.

Carl Smith, U. S. Geological Survey, Washington, D. C. December, 1912.

*Eugene A. Smith, University of Alabama, University, Ala.

George Otis Smith, U. S. Geological Survey, Washington, D. C. Aug., 1897.

Philip S. Smith, U. S. Geological Survey, Washington, D. C. Dec., 1909.

Warren Du Pré Smith, University of Oregon, Eugene, Oregon. Dec., 1909.

W. S. Tangier Smith, Lodi, Cal. June, 1902.

*John C. Smock, Trenton, N. J.

Charles H. Smyth, Jr., Princeton University, Princeton, N. J. Aug., 1892.

Henry L. Smyth, Harvard University, Cambridge, Mass. August, 1894.

Robert Speight, Christ Church, Canterbury College, New Zealand. Dec., 1916.

Arthur Coe Spencer, U. S. Geological Survey, Washington, D. C. Dec., 1896.

*J. W. Spencer, 2019 Hillyer Place, Washington, D. C.

Frank Springer, U. S. National Museum, Washington, D. C. December, 1911.

Josiah E. Spurr, Bullitt Bldg., Philadelphia, Pa. December, 1894.

Joseph Stanley-Brown, 26 Exchange Place, New York, N. Y. August, 1892.

Timothy W. Stanton, U. S. National Museum, Washington, D. C. Aug., 1891.

Clinton Raymond Stauffer, University of Minnesota, Minneapolis, Minn. December, 1911.

Eugene Stebinger, Jr., U. S. Geological Survey, Washington, D. C. Dec., 1916.

Edward Steidtmann, University of Wisconsin, Madison, Wis. December, 1916.

Lloyd William Stephenson, U. S. Geological Survey, Washington, D. C. December, 1911.

*John J. Stevenson, 215 West 101st St., New York, N. Y.

Ralph Walter Stone, U. S. Geological Survey, Washington, D. C. Dec., 1912.

George Willis Stose, U. S. Geological Survey, Washington, D. C. Dec., 1908.

Charles K. Swartz, Johns Hopkins University, Baltimore, Md. Dec., 1908.

Stephen Taber, University of South Carolina, Columbia, S. C. Dec., 1914.

Joseph A. Taff, 781 Flood Building, San Francisco, Cal. August, 1895.

Mignon Talbot, Mount Holyoke College, South Hadley, Mass. Dec., 1913.

James E. Talmage, University of Utah, Salt Lake City, Utah. Dec., 1897.

Frank B. Taylor, Fort Wayne, Ind. December, 1895.

*James E. Todd, 1224 Rhode Island St., Lawrence, Kans.

Cyrus Fisher Tolman, Jr., Leland Stanford, Jr., University, Stanford University, Cal. December, 1909.

Arthur C. Trowbridge, State University of Iowa, Iowa City, Iowa. December, 1913.

*Henry W. Turner, 209 Alaska Commercial Building, San Francisco, Cal.

William H. Twenhofel, University of Wisconsin, Madison, Wis. Dec., 1913.

Mayville William Twitchell, State Geological Survey, Trenton, N. J. December, 1911.

Joseph B. Tyrrell, Room 534, Confederation Life Building, Toronto, Canada. May, 1889.

Johan A. Udden, University of Texas, Austin, Texas. August, 1897.

Edward O. Ulrich, U. S. Geological Survey, Washington, D. C. Dec., 1903.

Joseph B. Umpleby, U. S. Geological Survey, Washington, D. C. Dec., 1913.

*Warren Upham, Minnesota Historical Society, Saint Paul, Minn.

*Charles R. Van Hise, University of Wisconsin, Madison, Wis.

Frank Robertson Van Horn, Case School of Applied Science, Cleveland, Ohio. December, 1898.

Gilbert van Ingen, Princeton University, Princeton, N. J. December, 1904.

T. Wayland Vaughan, U. S. Geological Survey, Washington, D. C. Aug., 1896.

Arthur Clifford Veach, 7 Richmond Terrace, Whitehall, S. W., London, England. December, 1906.

*Anthony W. Vogdes, 2425 First St., San Diego, Cal.

*M. Edward Wadsworth, School of Mines, University of Pittsburgh, Pittsburgh, Pa.

*Charles D. Walcott, Smithsonian Institution, Washington, D. C.

Thomas L. Walker, University of Toronto, Toronto, Canada. Dec., 1903.

Charles H. Warren, Massachusetts Institute of Technology, Boston, Mass. December, 1901.

Henry Stephens Washington, Geophysical Laboratory, Washington, D. C. August, 1896.

Thomas L. Watson, University of Virginia, Charlottesville, Va. June, 1900.

Charles E. Weaver, University of Washington, Seattle, Wash. Dec., 1913.

Walter H. Weed, 29 Broadway, New York, N. Y. May, 1889.

Carroll H. Wegemann, U. S. Geological Survey, Washington, D. C. Dec., 1912.

Samuel Weidman, Wisconsin Geological and Natural History Survey, Madison, Wis. December, 1903.

Stuart Weller, University of Chicago, Chicago, Ill. June, 1900.

Lewis G. Westgate, Ohio Wesleyan University, Delaware, Ohio. Aug., 1894.

Edgar T. Wherry, U. S. National Museum, Washington, D. C. Dec., 1915.

David White, U. S. National Museum, Washington, D. C. May, 1889.

*Israel C. White, Morgantown, W. Va.

George Reber Wieland, Yale University, New Haven, Conn. December, 1910.

Frank A. Wilder, North Holston, Smyth County, Va. December, 1905.

*Edward H. Williams, Jr., Woodstock, Vt.

*Henry S. Williams, Cornell University, Ithaca, N. Y.

Ira A. Williams, Oregon School of Mines, Corvallis, Ore. December, 1905.

Merton Yarwood Williams, Geological Survey, Ottawa, Canada. Dec., 1916.

Bailey Willis, Leland Stanford, Jr., University, Cal. December, 1889.

Alfred W. G. Wilson, Department of Mines, Ottawa, Canada. June, 1902.

Morley Evans Wilson, Geological Survey, Ottawa, Canada. December, 1916.

Alexander N. Winchell, University of Wisconsin, Madison, Wis. Aug., 1901.

*Horace Vaughn Winchell, First National Society Bldg., Minneapolis, Minn.

*Arthur Winslow, 131 State St., Boston, Mass.

John E. Wolff, Harvard University, Cambridge, Mass. December, 1889.

Joseph E. Woodman, New York University, New York, N. Y. Dec., 1905.

Robert S. Woodward, Carnegie Institution of Washington, Washington, D. C. May, 1889.

Jay B. Woodworth, Harvard University, Cambridge, Mass. December, 1895.

Charles Will Wright, Ingurtosu, Arbus, Sardinia, Italy. December, 1909.

Frederic E. Wright, Geophysical Laboratory, Carnegie Institution, Washington, D. C. December, 1903.

*G. Frederick Wright, Oberlin Theological Seminary, Oberlin, Ohio.

George A. Young, Geological Survey of Canada, Ottawa, Canada. Dec., 1905.

Victor Ziegler, Colorado School of Mines, Golden, Colo. December, 1916.

CORRESPONDENTS DECEASED

Herman Credner. Died July 22, 1913.
A. Michel-Lévy. Died September, 1911.
H. Rosenbusch. Died January 20, 1914.
Edward Suess. Died April 20, 1914.
Th. Tschernyschew. Died Jan. 15, 1914.
Ferdinand Zirkel. Died June 11, 1912.

FELLOWS DECEASED

*** Indicates Original Fellow (see article III of Constitution)**

*Chas. A. Ashburner. Died Dec. 24, 1889.
Alfred E. Barlow. Died May 28, 1914.
Charles E. Beecher. Died Feb. 14, 1904.
Albert S. Bickmore. Died Aug. 12, 1914.
Wm. Phipps Blake. Died May 21, 1910.
Amos Bowman. Died June 18, 1894.
Ernest R. Buckley. Died Jan. 19, 1912.
*Samuel Calvin. Died April 17, 1911.
Frank. R. Carpenter. Died April 1, 1910.
*J. H. Chapin. Died March 14, 1892.
*Edward W. Claypole. Died Aug. 17, 1901.
*Theo. B. Comstock. Died July 26, 1915.
George H. Cook. Died Sept. 22, 1889.
*Edward D. Cope. Died April 12, 1897.
Antonio Del Castillo. Died Oct. 28, 1895.
*James D. Dana. Died April 14, 1895.
Charles A. Davis. Died April 9, 1916.
George M. Dawson. Died March 2, 1901.
Sir J. Wm. Dawson. Died Nov. 19, 1899.
Orville A. Derby. Died Nov. 27, 1915.
Clarence E. Dutton. Died Jan. 4, 1912.
*William B. Dwight. Died Aug. 29, 1906.
*George H. Eldridge. Died June 29, 1905.
*Samuel F. Emmons. Died March 28, 1911.
Wm. M. Fontaine. Died April 29, 1913.
*Albert E. Foote. Died October 10, 1895.
*Persifor Frazer. Died April 7, 1909.
*Homer T. Fuller. Died Aug. 14, 1908.
N. J. Giroux. Died November 30, 1891.
*Christopher W. Hall. Died May 10, 1911.
*James Hall. Died August 7, 1898.
John B. Hatcher. Died July 3, 1904.
*Robert Hay. Died December 14, 1895.
C. Willard Hayes. Died Feb. 9, 1916.
*Angelo Heilprin. Died July 17, 1907.
Eugene W. Hilgard. Died Jan. 8, 1916.
Frank A. Hill. Died July 13, 1915.
*Joseph A. Holmes. Died July 13, 1915.
David Honeyman. Died October 17, 1889.
*Edwin E. Howell. Died April 16, 1911.
*Horace C. Hovey. Died July 27, 1914.
Thomas S. Hunt. Died Feb. 12, 1892.
*Alpheus Hyatt. Died Jan. 15, 1902.
Thomas M. Jackson. Died Feb. 3, 1912.
*Joseph F. James. Died March 29, 1897.
Wilbur C. Knight. Died July 28, 1903.
Ralph D. Lacoe. Died February 5, 1901.
J. C. K. Laflamme. Died July 6, 1910.
Daniel W. Langton. Died June 21, 1909.
*Joseph Le Conte. Died July 6, 1901.
*J. Peter Lesley. Died June 2, 1903.
Henry McCalley. Died Nov. 20, 1904.
*W J McGee. Died September 4, 1912.
Oliver Marcy. Died March 19, 1899.
Othniel C. Marsh. Died March 18, 1899.
*Fred. J. H. Merrill. Died Nov. 29, 1916.
James E. Mills. Died July 25, 1901.
*Henry B. Nason. Died January 17, 1895.
*Peter Neff. Died May 11, 1903.
*John S. Newberry. Died Dec. 7, 1892.
William H. Niles. Died Sept. 12, 1910.
*Edward Orton. Died October 16, 1899.
*Amos O. Osborn. Died March, 1911.
*Richard Owen. Died March 24, 1890.
Samuel L. Penfield. Died Aug. 14, 1906.
David P. Penhallow. Died Oct. 20, 1910.
*Franklin Platt. Died July 24, 1900.
William H. Pettee. Died May 26, 1904.
*John W. Powell. Died Sept. 23, 1902.
*Chas. S. Prosser. Died Sept. 11, 1916.
*Israel C. Russell. Died May 1, 1906.
*James M. Safford. Died July 3, 1907.
*Charles Schaeffer. Died Nov. 23, 1903.
*Nathaniel S. Shaler. Died April 10, 1906
William J. Sutton. Died May 9, 1915.
Ralph S. Tarr. Died March 21, 1912.
William G. Tight. Died Jan. 15, 1910.
Charles Wachsmuth. Died Feb. 7, 1896
Thomas C. Weston. Died July 20, 1910.
Theodore G. White. Died July 7, 1901.
*Robert P. Whitfield. Died April 6, 1910.
*George H. Williams. Died July 12, 1894.
*J. Francis Williams. Died Nov. 9, 1891.
Arthur B. Wilmott. Died May 8, 1914.
*Alexander Winchell. Died Feb. 19, 1891
*Newton Winchell. Died May 1, 1914.
Albert A. Wright. Died April 2, 1905.
William S. Yeates. Died Feb. 19, 1908.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 28, PP. 189-234 MARCH 31, 1917
PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY

PROCEEDINGS OF THE EIGHTH ANNUAL MEETING OF THE PALEONTOLOGICAL SOCIETY, HELD AT ALBANY, NEW YORK, DECEMBER 27, 28, AND 29, 1916.

R. S. Bassler, *Secretary*

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Session of Wednesday, December 27

The general session of the Society was called to order by President Rudolf Ruedemann at 2.30 p. m., December 27, in the west Archeology Mezzanine of the State Education Building. After welcoming the members to the new State Museum, Doctor Ruedemann spoke of the great and beneficent influence that has been exerted on the science by the paleontologists who have lived and worked at Albany and by others who received their training there and made honored places for themselves elsewhere. President Ruedemann then called for the report of the Council as the first matter of business.

REPORT OF THE COUNCIL

To the Paleontological Society in eighth annual meeting assembled:

The first regular meeting of this year's Council was held at Washington, D. C., December 30, 1916, on the adjournment of the Society. Between this and the second meeting of the Council, just before the present session, the business of the Society has been conducted by correspondence. A résumé of the administration for the eighth year of the Society is given in the following reports of officers.

SECRETARY'S REPORT

To the Council of the Paleontological Society:

Meetings.—The proceedings of the seventh annual meeting of the Society, held at Washington, D. C., December 29 and 30, 1915, have been published in volume 27 of the Bulletin of the Geological Society of America, pages 139 to 174. Besides this publication, the scientific papers of the Society published in this Bulletin during the year are seven in number and occupy a portion of number 2, all of number 3, and part of number 4 of volume 27. Copies of the Proceedings and these seven papers have been distributed to the members. An article by Prof. Joseph Barrell on "The influence of Silurian-Devonian climates on the rise of air-breathing vertebrates," published in number 2, volume 27, of the Bulletin of the Geological Society of America, was deemed of such importance to our own Society that copies were secured for all the members.

The Council's proposed nomination for officers and announcement that the eighth annual meeting of the Society would occur at Albany, New York, at the invitation of President John H. Finley, of the University of the State of New York, and Dr. John M. Clarke, Director of the New York State Museum, were forwarded to the members on March 20, 1916. Since that time the members have received all the announcements, preliminary programs, etcetera, of the Geological Society of America, in addition to those of our own Society.

Membership.—During the year the Society has lost by death Dr. Charles S. Prosser, Professor of Geology at the Ohio State University, who died September 11, 1916.

The thirteen candidates elected at the seventh annual meeting have been placed on the rolls, making the present enrollment 176. Five candidates are under consideration for the present meeting. Three members of the Society were elected to Fellowship in the Geological Society of America at the election just concluded.

Pacific Coast Section.—The seventh annual meeting of the Pacific Coast Section of the Society was held at Stanford University April 29, 1916, with Dr. J. C. Merriam presiding and twenty-four members and visitors present. Seventeen papers, dealing with both the Vertebrate and Invertebrate Paleontology and Stratigraphy of the West Coast especially, were read at this meeting. The minutes of this section are printed on pages 223 to 234 of this Bulletin.

Respectfully submitted,
R. S. BASSLER,
Secretary.

WASHINGTON, D. C., *December 27*, 1916.

TREASURER'S REPORT

To the Council of the Paleontological Society:

The Treasurer begs to submit the following report of the finances of the Society for the fiscal year ending December 26, 1916:

RECEIPTS

Cash on hand December 20, 1915	$383.17	
Membership fees (1915), 1	3.00	
Membership fees (1916), 78	234.55	
Interest, Connecticut Savings Bank	6.00	
		$626.72

EXPENDITURES

Treasurer's office:			
Postage	$3.00		
		$3.00	
Secretary's office:			
Secretary's allowance	$50.00		
Expenses	40.26		
		90.26	
Geological Society of America:			
For printing separates	$35.55		
		35.55	
Pacific Coast Section:			
Secretary's expenses	$16.26		
		16.26	
			$145.07
Balance on hand December 26, 1916			$481.65
Net increase in funds			$98.48
Outstanding dues (1915), 1		$3.00	
Outstanding dues (1916), 8[1]		24.00	
			27.00

Respectfully submitted,
RICHARD S. LULL,
Treasurer.

NEW HAVEN, CONNECTICUT, *December* 26, 1916.

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[1] Of this number, one member is a prisoner of war in France and a second is with the Canadian expeditionary force at the front.

APPOINTMENT OF AUDITING COMMITTEE

Next in order of business was the appointment of a committee to audit the Treasurer's accounts. W. H. Twenhofel and M. W. Twitchell were appointed after a motion to this effect had been voted on by the members.

ELECTION OF OFFICERS AND MEMBERS

The next matter of business was the announcement of the election of officers for 1917 and of new members. The results of the ballots were as follows:

OFFICERS FOR 1917

President:

J. C. **Merriam**, Berkeley, Cal.

First Vice-President:

W. D. **Matthew**, New York City

Second Vice-President:

E. W. **Berry**, Baltimore, Md.

Third Vice-President:

A. W. **Grabau**, New York City

Secretary:

R. S. **Bassler**, Washington, D. C.

Treasurer:

R. S. **Lull**, New Haven, Conn.

Editor:

C. R. **Eastman**, New York City

NEW MEMBERS

Joseph A. Cushman, Sharon, Mass.
Carl O. Dunbar, Peabody Museum, New Haven, Conn.
Richard M. Field, Jamaica Plains, Mass.
Wilber I. Robinson, Vassar College, Poughkeepsie, N. Y.
Edward J. Whittaker, Geological Survey, Ottawa, Canada.

The President then called the attention of the Society to three nominations for membership which had been received too late for the printed ballot and which had been acted on favorably by the Council. Following a motion by Dr. John M. Clarke and the unanimous vote by the members, the Secretary was instructed to cast the ballot of the Society for the election to membership in the Society of the following three nominees:

Henry M. Du Bois, A. B. (1913), A. M. (1914) Indiana University. Assistant in Paleontology, University of Illinois, Urbana, Illinois. Engaged in ecological and stratigraphic paleontology. Proposed by T. E. Savage and E. R. Cumings.

John B. Reeside, Jr., A. B. (1911), Ph. D. (1915) Johns Hopkins University. Assistant Geologist, United States Geological Survey. Engaged in study of Cretaceous invertebrates and stratigraphy. Proposed by T. W. Stanton and R. S. Bassler.

Clifton J. Sarle, B. S. (1902), M. S. (1903) University of Rochester, Ph. D. (1906) Yale University. Professor of Geology, University of Arizona, Tucson, Arizona. Engaged in study of Paleozoic invertebrates, especially problematic forms. Proposed by George H. Chadwick and R. S. Bassler.

PRESENTATION OF GENERAL PAPERS ON VERTEBRATE PALEONTOLOGY

Doctor Matthew then took the chair and the reading of papers on vertebrate paleontology of a general nature was commenced. The first paper, which was a very important and interesting one, dealing with the stratigraphy and vertebrate paleontology of the Pliocene, was illustrated by lantern slides, showing the correlation and lists of the mammalian faunas of the various formations.

PLIOCENE MAMMALIAN FAUNAS OF NORTH AMERICA

BY JOHN C. MERRIAM

(*Abstract*)

Within the past decade we have come to know Pliocene mammalian faunas in at least six important localities of the Pacific Coast and Great Basin provinces. These faunas represent two or more zones. A third zone is possibly represented by faunas known at localities not included in the six stations to which reference has been made.

The Pacific Coast and Great Basin Pliocene faunas have many faunal elements known also in the Pliocene of the middle and southern Great Plains region and in that of the South Atlantic provinces. Although no one of these North American faunas is as yet known in full, sufficient evidence is at hand to advance somewhat our knowledge of these relationships and relative age.

The Pliocene mammal faunas of North America contain a considerable number of recently discovered elements, appearing also in late Tertiary formations of Asia and Europe. An assembling of evidence now available makes possible some advance in our knowledge of world relationships of Pliocene faunas.

This instructive paper was followed by two very interesting accounts of the geologic work and the results of studies on the Tertiary of western Nebraska by Doctor Matthew and Professor Osborn.

LATER TERTIARY FORMATIONS OF WESTERN NEBRASKA

BY W. D. MATTHEW

GEOLOGIC TOUR OF WESTERN NEBRASKA

BY H. F. OSBORN

A motion to the effect that the Vertebrate Section hold adjourned meetings at the American Museum of Natural History, in New York City, December 28, 29, as arranged in the program, was carried.

At 5 o'clock the session adjourned to attend a public address given in Chancellor's Hall, entitled

THE PULSE OF LIFE

BY R. S. LULL

Wednesday evening the members attended the annual dinner with the Fellows of the Geological Society of America at the Ten Eyck Hotel.

Session of Thursday, December 28

Thursday morning, at 9.30 o'clock, the Section of Invertebrate and General Paleontology met, with Vice-President Foerste in the chair.

The first paper on the program was of especial general interest on account of its bearing on the antiquity of man in America. It was presented by the author and was discussed by Messrs. Sellards, Schuchert, and Berry.

PLANTS ASSOCIATED WITH HUMAN REMAINS AT VERO, FLORIDA

BY E. W. BERRY

(*Abstract*)

The significance of the plants found at Vero, Florida, in association with human remains and a Pleistocene vertebrate fauna was discussed. These plants include numerous fragments of leaves and a great variety of fruits and seeds preserved in an impure peat, and seem to indicate slightly different physical conditions and vegetation from that prevailing at the present time in this region.

Discussion

Mr. E. H. Sellards: Mr. Berry's contribution to the discussion of the age of the human remains at Vero is very welcome. One of the pleasant features in connection with these discoveries is the willing cooperation which has been extended by geologists, anthropologists, and paleontologists, and it would seem that out of these combined efforts we are really making progress in assembling the evidence.

It now seems pretty definitely established that the fossils of the deposits are those which we commonly assign to the Pleistocene period. I speak now of the fossils as such, omitting for the moment consideration of how or by what means they may have reached their present location. If it is true that the fossils are those of the Pleistocene, we then have to consider whether, on the one hand, the fossils are secondary and have been fossilized elsewhere and washed to their present location, or whether the human remains and artifacts are themselves not normal to the deposit, but have been introduced by recent burial or otherwise. That the fossils of strata 2 and 3 are secondary can not be maintained. Of mammals, we have taken from these deposits a practically complete and very fragile skull of a tapir, an equally fragile and approximately complete skull of an extinct wolf, as well as about thirty bones probably of the same individual; a considerable part of the skull of a mastodon; a considerable part of the skeleton of the extinct armadillo, *Chlamytherium*, as well as a large number of other mammalian bones, too perfect and too delicate to represent secondary fossils. Of birds, there have been obtained a number of wing bones of an extinct stork, as well as bones representing six or seven other species. Of turtles, which are numerous and varied, there have been obtained complete carapaces which are much too delicate to have been moved about after being fossilized. Lastly, the fossil leaves, of course, can not be secondary, and the testimony of these as presented by Mr. Berry is consistent with that of the other fossils, indicating the Pleistocene age of the deposits.

It is equally certain that the human remains and artifacts can not represent recent burials. The bones known to belong to a single individual are scattered in a way that excludes their interpretation as a burial. The second bone from skeleton number 2, found in place, was the proximal part of the shaft of the left femur. This was taken in April, 1916. In the following June, after having excavated farther into the bank, a part of the distal part of the shaft of this bone was obtained, the distance separating the two pieces being 8 feet. The break is clean and the fit perfect. The bone consisting of these two pieces is illustrated in the Eighth Annual Report of the Florida Geological Survey (plate 19, figure 3). The left ulna and left radius, both incomplete, are separated by a distance of 5 feet. The skull, of which scarcely half was obtained, was secured in the form of fragments extending over an area of not less than 6 by 3 feet. The distribution of the artifacts throughout the deposits is inconsistent with the idea that they represent burials. The pieces of pottery, as well as the bone implements, have been obtained one by one as the excavating progressed. Their distribution is general throughout the deposit, although they are more abundant near the base than elsewhere.

I am interested also in Mr. Berry's observation that there is probably no large time interval between strata numbers 2 and 3, since it agrees with a suggestion made by me in the paper last published relating to these deposits (Journal of Geology, volume 25, page 21, January-February, 1917). Personally I feel very much gratified at Mr. Berry's contribution to the discussion.

Following Professor Berry's paper was an interesting account of fossil rock-boring animals, read by the author and discussed by Messrs. Berry, Schuchert, Field, Bassler, and Vaughan.

GEOLOGIC SIGNIFICANCE OF FOSSIL ROCK-BORING ANIMALS

BY A. L. BARROWS

(*Abstract*)

Among the marine boring and burrowing animals of the present day there are certain genera of sea-urchins, *Echinus* and *Strongylocentrotus*, and pelecypod genera, *Adula*, *Lithodomus*, *Pholadidea*, and *Parapholas*, members of which habitually bore into rock and do not enter less compact materials, liable to crumble or collapse. These may be distinguished from mud and sand burrowers and from occasional borers into rock, both recent and fossil, by certain morphologic modifications known to be associated with the rock-boring habit, or by characters of the bore itself, showing that it was made in indurated rock rather than in sand or mud. The origin of the boring habit and the method of boring also strengthen confidence placed in the starfish and mytilid borers, and, to a certain extent, in some of the more highly specialized pholad genera as determiners of an indurated condition of the substratum in which they lived, when preserved as fossils in their native holes. The occurrence of fossil nestling shells in the holes of borers is even better evidence of the induration of the rock when the borers lived than the presence of the remains of the boring animals themselves. There is evidence to suggest that the exposed ledges which these borers and nestlers entered were located in access to fresh ocean water at no very great depth. Borers and nestlers may also be indicative of faults and disconformities, and may constitute the only relics of the previous fauna of the region which they occupied. In the history of deposition in a given locality the full significance of the former existence of an exposed ledge of rock must depend on further information concerning the faunas of the beds in question, the texture of the rock, their stratigraphic relations and correlations with other beds, and the recurrence of similar conditions in these respects over a wide range of territory.

The following paper on new genera of Paleozoic corals was then given and illustrated by sketches. Discussed by G. H. Chadwick, with reply by the author.

NEW GENERA OF CORALS OF THE FAMILY OF CYATHOPHYLLIDÆ

BY AMADEUS W. GRABAU

(*Abstract*)

The genera discussed were *Pinnatophyllum*, *Stereophyllum*, *Merophyllum*, and *Blothromissum*, among the simple *Cyathophyllidæ*, and *Pristiphyllum* and *Calvinastræa* among the compound ones. The structure, genetic relations, distribution, and migration were considered.

A second paper on fossil corals and their bearing on Tertiary paleogeography was presented next and was illustrated by lantern slides. Discussed by Messers. Schuchert, Grabau, and the author.

REEF CORAL FAUNA OF CARRIZO CREEK, IMPERIAL COUNTY, CALIFORNIA, AND ITS SIGNIFICANCE

BY T. WAYLAND VAUGHAN

(*Abstract*)

The paper was an abstract of a short monograph entitled "The reef-coral fauna of Carrizo Creek, Imperial County, California, and its geologic significance," in press as Professional Paper 98-T of the United States Geological Survey.

Carrizo Creek, along which the corals were obtained, is in the western part of Imperial Valley, about 15 miles north of the Mexican boundary and about 20 miles southwest of the southern end of Salton Sea. The geologic section comprises (1) a basal complex of granites and metamorphic rocks, (2) andesite extruded over the eroded surface of the basal complex, (3) a marine sedimentary series of clays, sands, and conglomerates which rest on the eroded surface of the underlying rocks and in the lower part of which are abundant reef corals, and (4) Pleistocene lake beds.

The conclusions resulting from the study are as follows:

1. The Carrizo Creek reef-coral fauna is Atlantic, not Pacific, in its affinities.

2. During Eocene and Oligocene time there was connection between the Atlantic and Pacific oceans across Central America, and there was no sharp differentiation between the Atlantic and Pacific fauna.

3. Upper Oligocene (Apalachicolan) time was closed by diastrophic and other geologic events of profound importance, which separated the Atlantic from the Pacific Ocean by a land area extending from North to South America. During Miocene time the sharp differentiation between the Atlantic and Pacific faunas took place, largely by the extinction of the Pacific elements in the former fauna.

4. The Pliocene coral fauna of Florida is purely Atlantic in its affinities, and since Pliocene time there has been only minor modification of the coral fauna in the western Atlantic, the Gulf of Mexico, and the Caribbean Sea.

5. The Carrizo Creek fauna is related to the Pliocene and post-Pliocene faunas of Florida and the West Indies and can scarcely be older than Lower Pliocene.

6. Subsequent to the differentiation between the Atlantic and the Pacific faunas there was interoceanic connection in Upper Miocene of Pliocene time which permitted the Atlantic fauna to extend into the Gulf of California and up to its head, and conditions which we do not understand excluded the Pacific fauna from that area.

7. The locus of the inferred interoceanic connection is not known. It was probably in the region of the Isthmus of Tehuantepec or farther southeastward.

The results of a study of the brachiopod genus Platystrophia were presented by the author, with lantern slide illustrations. Discussed by Messrs. Ulrich and Schuchert.

SOME MORPHOLOGICAL VARIATIONS IN PLATYSTROPHIA

BY MRS. EULA D. MC EWAN[1]

(*Abstract*)

A study of the morphological variations of Platystrophia shows that the Ordovician forms have developed along three lines, two of which the writer calls the Uniplicate and the Bifurate types; the third has been called the Triplicate type.

The *Uniplicate* type has one plication in the sinus and is called *P. uniplicata.* The *Bifurate* type has one plication in the sinus in the nepionic stage; later this plication bifurcates. A great many individuals do not go beyond this stage; there are greater numbers in which a plication is intercalated in a median position. This is called *P. trentonensis.*

The first member of a third line of development passes through a uniplicate stage. After a short interval of growth a plication is intercalated in the sinus on one side of the median plication. A great many individuals were found which do not go beyond this stage in development. Another species adds a second lateral plication in the sinus on the opposite side of the median plication.

All three types are found in the Trenton; the triplicate type is characteristic of the Maysville and Richmond.

The Maysville and Richmond species which were studied fall conveniently into three groups. The *Ponderosa Group* is characterized by large size; the *Low Fold Group* has a long hinge relative to the height and retained the low fold of the nepionic stage throughout its entire life history; the *High Fold Group* has a long hinge relative to the height and developes at an early stage a high compressed fold on which the plications tend to disappear.

Seven species are placed in the *Ponderosa Group*, five of which are new. Three species are placed in the *Low Fold Group.* *P. sublaticosta* n. sp. is shown to be the ancestor of *P. clarksvillensis* and *P. acutilirata*, which are the other two members of this group. Four species were placed in the *High Fold Group.* Three of the members lose the lateral plications of the fold and sinus. *P. unicostata* loses them by retardation in development, while *P. crassa* and *P. cypha* lose them by obsolescence. This shows that the supposed identity of *P. unicostata* and *P. cypha* does not rest on sufficient grounds. Index curves do not support the supposed development of *P. cypha* from *P. unicostata.* It has been held that *P. acutilirata* developed from *P. laticosta* through *P. unicostata* and *P. cypha.* The stratigraphic position of these forms and the long hinge of *P. cypha* suggest this. These two species, however, represent the culmination of a development toward the excessive elevation of the fold, accompanied by the loss of the lateral plications of the fold and sinus. It is improbable that forms of this type should give rise to a species which retains

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[1] Introduced by A. W. Grabau.

the low fold and strong lateral plications throughout its entire life history. Index curves and the characters common to both and their common order of appearance suggest a common origin, and *P. sublaticosta* occupies the right stratigraphic position and has all the characters necessary to be an ancestor of these two species.

The Secretary next presented a discussion on American Silurian ostracoda for the author. Illustrated by specimens and lantern slides; discussed by Messrs. Grabau, Schuchert, Ulrich, and Bassler.

THE OSTRACODA AS GUIDE FOSSILS IN THE SILURIAN DEPOSITS OF THE APPALACHIAN REGION

BY E. O. ULRICH

(*Abstract*)

The exact time relations of the Silurian deposits of the Appalachian Valley with respect to the standard section of the interior of the continent have long been conjectural, but it has always been recognized that the ostracoda, on account of their exceeding abundance and excellent preservation, would seem better for correlation than almost any other group of fossils. Another reason for the use of this group in correlation is that the same species will occur indiscriminately in limestone, shale, or sandstone, and so well preserved in each case that exact determinations are possible. Even when preserved as molds in sandstone a gutta-percha squeeze will give all the essential features of the carapace.

Hitherto less than half a dozen Appalachian Silurian ostracoda have been recognized, but as a result of the present work no less than twenty-seven new genera and several hundred species are known. An interesting feature has been the discovery that species and genera otherwise quite similar can readily be distinguished by the form and position of the swelling on one of the lobes of certain individuals which are considered the female forms. On the assumption that this swelling is the brood pouch, the long controversy as to which is the anterior and posterior end of these Paleozoic ostracoda can now be settled, since the swelling always marks the posterior end of the carapace.

REPORT OF THE AUDITING COMMITTEE

At this point the Auditing Committee gave notice that their report on the accounts of the Treasurer was ready. The correctness of the accounts was attested by the committee and the Society voted that their report be accepted.

The reading of papers was then resumed with the presentation of the following, which was illustrated by lantern slides. Discussed by Messrs. Mook, Schuchert, and Twenhofel.

AGE OF THE AMERICAN MORRISON AND EAST AFRICAN TENDAGURU FORMATIONS

BY CHARLES SCHUCHERT

(*Abstract*)

The very interesting dinosaur-bearing Morrison formation is underlain by the Sundance and overlain by the equivalent of the Washita. The latter is the last series of the Comanchian, though some European stratigraphers regard it as of early Upper Cretaceous time. On the other hand, the Sundance is regarded by some paleontologists as of early Upper Jurassic age and by others as late Upper Jurassic; the evidence of the ammonites and saurians appears to indicate the Kimmeridgian rather than the Oxfordian. Between the Sundance and the Morrison, it is now widely held, there is a time break and the two series of deposits overlap from opposite directions. It appears that during this interval there occurred the Sierra Nevada orogeny, and accordingly, on the basis of diastrophism, the Morrison should be of Comanchian age. The floral and faunal evidence of the Morrison is also rather in harmony with this conclusion, and is further supported by that of the East African Tendaguru series, which has Jurassic and Lower Cretaceous marine and dinosaur faunas. This conclusion also falls in line with the decision of the Committee on Geological Names of the United States Geological Survey, who early in 1916 deemed the evidence sufficient to warrant the classification of the Morrison as of Lower Cretaceous age.

The excellent results obtained by special methods of study were described in the next paper, which was illustrated by photographs and a stereoscope. Discussed by A. F. Foerste.

EXTERNAL STRUCTURE OF STEGANOBLASTUS AS REVEALED THROUGH GUM MOUNTINGS AND PHOTOMICROGRAPHIC STEREOGRAMS

BY GEORGE H. HUDSON

(*Abstract*)

The writer has made a complete analysis of the surface with all sutures clearly revealed. It has large deltoids, sagittate, with a small group of plates in the sinus. The distal extensions of the deltoids pass into the sinus of the radials by a diagonal and adjustable sliding suture, as in Pentremites only the deltoids reach nearer the arm tip. The deep groovings on the plate surfaces were for branching epispires, which were protected by a forest of spines. The floor and cover plates rested directly against the deltoid, and under these was a double sublancet plate. The "pore plates" had no pores, but were covered with spines.

A second study by the same author, in which the same methods of research were employed, was then presented.

SOME STRUCTURAL FEATURES OF A FOSSIL EMBRYO CRINOID

BY GEORGE H. HUDSON

(*Abstract*)

A fossil embryo crinoid is described as a new genus and species and named *Embryocrinus problematicus.* The arm structure, as shown by enlargements (× 20) taken through cover-glass and gum mounting, is seen to consist of a linear series of thin, irregularly formed discs or lunate pieces of stereom, in an otherwise fleshy extension of epidermal or associated tissues. The structure revealed is precisely like that of the spines and spinelets of *Urasterella medusa*, as shown in plates accompanying the report of the New York State Director of Science and State Museum for 1915.

The methods of study and the progress made in the preparation of a monograph on American Tertiary Bryozoa were outlined by the junior author. Illustrated by specimens and lantern slides; discussed by R. M. Field.

METHODS OF STUDY AND THE CLASSIFICATION OF AMERICAN TERTIARY BRYOZOA

BY F. CANU AND R. S. BASSLER

(*Abstract*)

The junior author showed, with the aid of specimens and lantern slides, the methods of collecting, the preparation for study, and the characters employed in classification of American Tertiary bryozoa now under monographic study. Until recent years the post-Paleozoic bryozoa have been considered more as perforated stones than as well organized creatures in which the perforations and ornamentation of their surface had definite physiological purposes. The relation between the morphological and skeletal variation and their physiological purposes was determined in the case of the fossil forms by the close study of the most nearly related living species. This study showed that (1) a family is characterized by having the same larval form, or, since the larva and ovicell are in rapport, by the same kind of ovicell; (2) that the genera differ from each other by possessing different functions. These functions, common to all bryozoa, are as follows:

1. Passage of eggs and escape of the larvæ (= rapport of the operculum and the ovicell).
2. Hydrostatic system and extrusion of the polypide (= form of the aperture and rapport of the operculum with the compensatrix).
3. Calcification and chitinization (= nature of the skeleton and of the frontal considered as immediate deposits of the endocyst).

At 1 p. m. the Society adjourned for luncheon.

PRESIDENTIAL ADDRESS

At 2.30 p. m. the Society convened to hear the address of the retiring President on the subject,

THE PALEONTOLOGY OF ARRESTED EVOLUTION

BY DR. RUDOLF RUEDEMANN

Following Doctor Ruedemann's address the presentation of papers on General and Invertebrate Paleontology was resumed. The first paper was a report of progress and was illustrated by lantern slides. Discussed by Charles Schuchert.

PRESENT STATUS OF AREAL MAPPING IN THE COASTAL PLAIN AND OF THE PALEONTOLOGIC INVESTIGATIONS IN THE COASTAL PLAIN, PANAMA, AND THE WINDWARD ISLANDS

BY T. WAYLAND VAUGHAN

(*Abstract*)

This paper presented in outline the purpose and plan of the studies in areal geology and paleontology in the Coastal Plain of the Atlantic and Gulf States, in the Canal Zone, and in the West Indies. The present status of the investigations was indicated by maps and tables, which were shown on the screen.

An interesting and ingenious interpretation of the stratigraphic relations of certain graptolite shales and continental deposits of Great Britain was given by Doctor O'Connell, who presented the following paper, illustrated by charts. Discussed by Messrs. Ruedemann, Grabau, Twenhofel, Schuchert, and Bassler.

WERE THE GRAPTOLITE-BEARING SHALES, AS A RULE, DEEP OR SHALLOW WATER DEPOSITS?

BY AMADEUS W. GRABAU AND MARJORIE O'CONNELL

(*Abstract*)

By most authors graptolite shales have been considered as deep water deposits. This interpretation is questioned on the following grounds: (1) An examination of the most important graptolite-bearing formations of Europe and of North America shows a vast preponderance of clastic material of very shallow water, if not of actually continental origin, the graptolite-bearing beds being very thin intercalations in each series. Often evidence of shallow water conditions is shown in the beds themselves. (2) The great scarcity of normal marine organisms and their very frequent absence in the beds between the graptolite layers negatives the marine origin of these sediments. (3) The improbability of graptolite remains sinking to the floor of the relatively deep ocean, especially where strong surface currents transport them, seems generally

not to have been considered. The interpretation of the graptolite beds as delta deposits formed near the mouths of large rivers and repeatedly flooded by the sea, resulting in the stranding on the mud-flats of the planktonic or epi-planktonic graptolites, will be discussed in the light afforded by such sections as those of the Moffat district of Scotland, the Scandinavian region, Bohemia, Wales, and North England, and the Hudson River region of North America.

A second paper on the subject of graptolites completed the program for the day. Discussed by Messrs. Grabau, Schuchert, and Chadwick.

GRAPTOLITE ZONES OF THE UTICA SHALE

BY RUDOLF RUEDEMANN

(*Abstract*)

Four zones have been distinguished in the Utica shale of the Upper Mohawk Valley and Black River Valley. The type section in the city of Utica is within the third zone; the fourth zone is found in the Black River Valley.

After deciding to attend the Symposium on Sedimentary Rocks, on the program of the Geological Society of America at 10 o'clock the following morning, the Society adjourned at 5.30 p. m.

At 8.15 o'clock the members convened in Chancellor's Hall of the Education Building and listened to the address of Dr. John M. Clarke, retiring President of the Geological Society of America.

At 9.15 the members joined the Fellows of the Geological Society of America at the smoker given at the University Club.

Session of Friday, December 30

The Society did not meet until 11.30 a. m. to continue the regular program on account of attendance at the Symposium on Sedimentary Rocks, under the auspices of the Geological Society of America. The subjects and speakers of this symposium were as follows:

SYMPOSIUM ON THE INTERPRETATION OF SEDIMENTARY ROCKS

THE PROBLEMS STATED

BY A. W. GRABAU

SIGNIFICANCE OF SEDIMENTARY RHYTHM

BY JOSEPH BARRELL

DIAGNOSTIC CHARACTERISTICS OF MARINE CLASTICS

BY E. M. KINDLE

CHARACTERISTICS OF CONTINENTAL CLASTICS AND CHEMICAL DEPOSITS

BY ELIOT BLACKWELDER

SIGNIFICANCE OF SORTING IN SEDIMENTARY ROCKS

BY E. W. SHAW

CHEMICAL AND ORGANIC DEPOSITS OF THE SEA

BY T. WAYLAND VAUGHAN

PRESENTATION OF PAPERS

The first paper of the Society's regular program was illustrated with lantern slides and was discussed by Messrs. Grabau, Bassler, Schuchert, Perdue, and Ulrich.

DEVONIAN AND BLACK SHALE SUCCESSION OF WESTERN TENNESSEE

BY CARL O. DUNBAR[1]

(*Abstract*)

Along the western valley of the Tennessee River the Lower Devonian begins with massive crystalline limestone of Coeymans age. The Decatur limestone, generally assigned to the Silurian, seems to be of this time. The New Scotland is represented by the well known and next higher Linden shale and limestone. Succeeding the Linden is the remnant of a southward extension of the New York Oriskany, for which the name Cypress Creek chert is proposed. This is a white or yellowish chert carrying *Spirifer arenosus*, *S. arrectus*, *Rensselæria ovoides*, *Plethorhyncha speciosa*, *Platyceras gebhardi*, etcetera.

The Cypress Creek is separated by a long time break from the Linden below and by a lesser one from the Camden chert above. The Camden chert is, then, very late Oriskany, and Savage's evidence that it goes unbroken into the Onondaga is thus corroborated.

The Camden chert is followed by the Chattanooga shale of the early Kinderhookian, and this in turn by the fossiliferous Ridgetop shale of later Kinderhookian time.

The next paper was presented extemporaneously by the author and illustrated by diagrams. Discussed by Charles Butts.

STRATIGRAPHIC RELATIONS OF THE TULLY LIMESTONE AND THE GENESEE SHALE OF NEW YORK AND PENNSYLVANIA

BY AMADEUS W. GRABAU

(*Abstract*)

The Tully limestone is a calcilutyte, the material of which was derived from the north, probably from coral or algal reefs which lay to the north of the

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[1] Introduced by Charles Schuchert.

present line of outcrop and have been since entirely removed by erosion. The Genesee shale is the mud brought by a river from the south into Pennsylvania and New York. The relationship of the two formations is that of replacing overlap--the muds gradually advancing from the south over the limestone. A recent study of the sections near Ithaca has furnished abundant evidence of such replacement.

A second paper on the classification of Silurian and Devonian corals was then given under the following title. Discussed by A. W. Grabau and the author.

AMERICAN DIPHYPHYLLOID CORALS

BY GEORGE H. CHADWICK

(*Abstract*)

A critical review of the half hundred specific names proposed for American Silurian and Devonian corals of the genera Diphyphyllum, Diplophyllum, Eridophyllum, Craspedophyllum, Synaptophyllum, and their allies, with discussion of the synonymy and classification within the group thus indicated. On the basis of well marked natural characters, it is shown that there are several definite generic types passing current under the name Diphyphyllum as broadly used, none of which are strictly referable to this European Carboniferous genus. Diplophyllum and Eridophyllum are each restricted to the type species, while the remaining forms are found to fall readily into Synaptophyllum, Craspedophyllum, or a Silurian group, possibly the Donacophyllum of Dybowski, and a small Devonian group, probably satellite to that. The unlike structures possessed by some of these genera indicate that their mutual affinities are of not nearer than family rank, so that the expression "diphyphyllid" is merely one of convenience for the present study.

Following this paper was one on methods of determining the attitude of strata, delivered by the author, and followed by remarks by E. B. Branson.

CRITERIA OF ATTITUDE IN BEDDED DEPOSITS

BY LANCASTER D. BURLING

(*Abstract*)

The criteria of attitude may be defined as those evidences by which a field observer may determine which is the bottom and which the top of a given bed, or series of beds, and something as to the history of past changes in the attitude of such a section. These criteria are classified and discussed, with bibliographic references to typical examples.

The final paper of the program was read by E. B. Branson in the absence of the author.

DEVONIAN OF CENTRAL MISSOURI; FAUNA OF THE COOPER LIMESTONE

BY DARLING K. GREGER[1]

(*Abstract*)

This paper includes a discussion of the region in which the formation occurs, its lithologic character and distribution as defined by Meek and Swallow, a description of the fauna and correlation of the formation.

The following papers were read by title:

ALBERTELLA FAUNA

BY CHARLES D. WALCOTT

SOME FUNDAMENTAL POINTS IN THE CLASSIFICATION OF TRILOBITES

BY PERCY E. RAYMOND

At 1.30 p. m. the Society adjourned.

SECTION OF VERTEBRATE PALEONTOLOGY

The minutes of the meeting of the vertebrate paleontologists with the general society at Albany, Wednesday afternoon, December 27, are given on a preceding page. At this session papers dealing with vertebrate paleontology, but of general interest, were presented, the special papers being reserved for the sectional meeting at New York City.

Session of Thursday, December 28 [1]

At the American Museum of Natural History, Thursday, December 28, at 10 o'clock, Doctor Matthew called the section to order for the reading of papers, the general business session being postponed to Friday afternoon. The following papers were presented:

FOSSIL MAMMALS FROM PORTO RICO

BY H. E. ANTHONY

(*Abstract*)

A discussion, illustrated by lantern slides, was given of the cave deposits of the island, in which were found the remains of ground-sloths, hystricomorph rodents, and a peculiar type of insectivore, besides birds, bats, etcetera, more nearly related to continental mammals. The deposit is of late Pliocene or early Pleistocene age.

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[1] Introduced by E. B. Branson.

[1] Prepared from the minutes of the session by W. D. Matthew and E. L. Troxell.

In the discussion which followed Dr. W. D. Matthew spoke of the importance of this new fauna, so different from that of the mainland. It is comparable to the relation of Madagascar and the African continent. Others who spoke on the subject were Messrs. Osborn, Gilmore, Gregory, Barbour, and Merriam.

SECOND REPORT OF THE COMMITTEE ON NOMENCLATURE OF SKULL ELEMENTS IN TETRAPODA

BY W. K. GREGORY

(*Abstract*)

Doctor Gregory read briefly from the report of the committee consisting of Doctor Broom, Professors Case, Moodie, Williston, and himself, illustrating his remarks by lantern slides. Through their conferences, carried on in part by correspondence, they were able to further the work of last year in the effort to secure a uniform system of names for skull elements in the several classes of vertebrates which would be generally acceptable and, so far as possible, in accord with the current usage of earlier writers.

The discussion was led by Messrs. Barnum, Brown, Merriam, Gregory, and the Chair, and the following points were brought out: An entirely harmonious nomenclature could never be devised, for there can not even be complete unanimity within the committee. However, a system, even though somewhat arbitrary, if once decided on, would ultimately be used by most morphologists and would be of the utmost value. It was recommended that the results so far attained should be printed for the reference of the members. A motion made by Doctor Merriam was passed, instructing the committee to continue its very useful services, and the Chair expressed the sentiment of appreciation of the Society for the faithful work on a very difficult, though extremely important, subject.

SESSION OF FRIDAY, DECEMBER 29

At 10 o'clock Friday morning, Doctor Matthew presiding, the program was resumed, and, excepting the hour for lunch, the time was filled with the reading and discussion of interesting papers until 4.30 p. m. The remaining papers were then read by title and the business session was called. The papers presented were as follows:

SOUTH CAROLINA MASTODON

BY F. B. LOOMIS

(*Abstract*)

A mastodon skeleton, which has been lying untouched for many years in the Museum of Amherst College, was rediscovered recently. It not only proved to be a nearly complete specimen, but probably a new form as well. Two complete tusks about 15 inches long were found in the lower jaws. The skeleton, which came from the (?) Ashley River beds of South Carolina and constitutes a part of the famous Shepard Collection, is now mounted in the Museum at Amherst.

This paper was illustrated by drawings and photographs and was discussed as follows by Messrs. Matthew, Brown, and Merriam: This skeleton may be of the species recently described by Doctor Hay as *Mammut progenium*, from a lower jaw out of the Aftonian beds of Iowa. The same species is recorded by Doctor Sellards in late Tertiary beds of Florida. Teeth and incomplete jaws from the phosphate beds of South Carolina may also belong to it. It is clearly a species distinct from the American mastodon.

HORNED ARTIODACTYL FROM THE TERTIARY OF NEBRASKA

BY R. S. LULL

(*Abstract*)

The expedition of 1914 from Yale University, while hunting over Marsh's old fields along the Niobrara River, found a very unusual horned animal, probably related to the giraffe, and certainly never known in America before. Several skulls were exhibited with the horn cores arising immediately back of the orbits. One specimen, probably a female, showed the merest beginning of a rudimentary horn, "a rectigradation." Since discovering the importance of this new material it is planned to send another party to the place to search for other specimens.

Doctor Merriam expressed great interest in anything like a horned artiodactyl of this type because of the abundance of antelopine forms in the Pacific Coast region. Doctor Sinclair felt the need of caution in any attempt to classify the Artiodactyla on the character of the horn cores. Doctor Matthew believed that its nearest relative was probably the Miocene genus *Blastomeryx*. of which it might be a descendant.

FELIDÆ OF RANCHO LA BREA

BY J. C. MERRIAM

(*Abstract*)

This was an interesting talk, with lantern slides, about the varieties of fossil cats from the asphalt deposits of California. The nature of the large saber-like canine teeth—in the manner of their succession, deciduous to permanent; their progressive protrusion, the great variation in the cusps of the molars and premolars, and the brachy- and dolichocephaly—was dwelt on. The differences in these respects would warrant separate species, according to our usual way of thinking; but, because in the hundreds of skulls at hand he finds a most perfect gradation, Doctor Merriam hesitates to separate the groups except in the most extreme cases.

Professor Osborn emphasized the importance to paleontology that this wonderful Rancho la Brea material should have fallen into the capable hands of Doctor Merriam.

GIGANTIC MEGATHERIUM FROM FLORIDA

BY W. D. MATTHEW

(*Abstract*)

During the summer of 1916 Mr. Heller presented to the Museum a small collection of fossil bones believed to be from Zolfo, Florida. Some of the remains are cetacean and may be of Tertiary age; the rest are apparently Pleistocene, and most of them, probably all, belong to a gigantic ground-sloth. The only complete bone is an astragalus; the proximal half of a femur, distal half of a radius, parts of tibia, and other unrecognizable fragments may very probably belong to the same individual, as they all agree well in characters with the skeleton of *Megatherium* described and figured by Owen and are about one-fifth larger in lineal dimensions.

The only point of especial interest about these remains is the size. *Megatherium* has been recorded from South Carolina, Georgia, Florida, Mississippi, and Texas, and no doubt its range extended throughout the Southern States in the Pleistocene; but I have found no record of any specimens materially larger than Owen's type. The present specimen, averaging one-fifth larger lineally, would have been about 1¾ as large in bulk or weight, and must have equaled or exceeded in bulk any known land mammal, living or extinct. It is to be hoped that the better specimens of this imposing beast may be secured through the active explorations now being conducted by the Florida State Geological Survey.

SKELETON OF DIATRYMA, A GIGANTIC BIRD OF THE LOWER EOCENE

BY W. D. MATTHEW AND WALTER GRANGER

(*Abstract*)

The discovery of a nearly complete skeleton of this extremely rare bird in the Wasatch formation of the Bighorn basin, Wyoming, was quite unexpected. It equaled the Moa in bulk, but had a gigantic head, with enormous compressed beak like the South American *Phororhachos*. It is not nearly related to any known type of bird.

AN OKLAHOMA PLEISTOCENE FAUNA

BY E. L. TROXELL

(*Abstract*)

A number of extinct animals were found in a refilled channel near Mulhall, Oklahoma. The list includes tapir, bison, mammoth, mastodon, horn, deer, giant sloth, and the ever-present turtle. The horns of the bison measure about 3 feet from tip to tip. Only one tapir has heretofore been reported from the Great Plains region. The collection, as a whole, indicates Osborn's second faunal zone, or else a forest group, the counterpart of the plains fauna of the *Equus* beds.

Dr. O. P. Hay added some very important points to the discussion of the *Bison*, of which he has made a special study. It is difficult to identify species on the horns alone, and yet there is little doubt but that *Bison latifrons*, with a spread of 6 feet and more, is distinct specifically from the modern animal, with short, inward curving horns, and it is quite impossible to assemble the intermediate forms in less than four or five harmonious groups. A recent discovery by Doctor Hay of the undoubted remains of *Bison* in association with those of *Camelus* marks the earliest known specimen in the Western Hemisphere.

FIRST RECORDED AMPHIBIAN FROM THE TERTIARY OF NEBRASKA

BY HAROLD J. COOK[1]

(*Abstract*)

Something over a year ago the writer was examining the dump of a series of excavations made in the Lower Pliocene Snake Creek beds by a party from an institution, and among other interesting things picked up what was clearly a portion of a jaw, of peculiar type. Both ends bore evidence of being freshly broken off, and so a careful search of the surface immediately surrounding was made, but without success.

The part secured was sent to Doctor Matthew for examination and comparisons, and apparently this specimen pertains to the group of giant salamanders not previously reported from the American Tertiary. Its closest known relative is the famous Oenigen fossil, now known as *Andrias scheuchzeri*, from the Upper Miocene of Switzerland. The present specimen greatly exceeds that form in size and was probably at least 5 feet in length, if we may judge from the size of the jaw. It is evidently a distinct form, for which the name *Plicagnathus matthewi* is proposed. The generic name is in reference to the folded appearance of the internal surface of the lower jaw and the specific name as a tribute to Dr. W. D. Matthew. Detailed descriptions and figures will shortly appear. The part preserved is 61 mm. long, 22 mm. deep, and 12 mm. in greatest transverse diameter.

Professor Loomis mentioned another in his possession; these two are probably the only known specimens.

LABYRINTHODONT FROM THE NEWARK SERIES

BY W. J. SINCLAIR

(*Abstract*)

The author exhibited the lower jaw of a gigantic Stegocephalian from the Brunswick horizon of the Newark of New Jersey and discussed its affinities.

Professor Lull, speaking from his experience and interest in the Triassic of the Connecticut Valley, emphasized the importance of anything which adds to our knowledge of the very meager fauna of the Newark series and called attention to the marked difference of the older Newark fauna from the Dinosaur fauna found in the upper beds.

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[1] Presented by W. D. Matthew.

FOSSIL VERTEBRATES FROM FLORIDA

BY E. H. SELLARDS

(*Abstract*)

This paper, illustrated by maps and diagrams, brought out additional facts of great interest on a subject discussed by Doctor Sellards in the July number of the American Journal of Science, concerning human bones and artifacts found in association with a number of extinct animals. The mineralized character of the bones, their scattered condition—in these respects resembling the other fossil animals—the undisturbed stratum, and the unbroken continuity of the overlying rock, all indicate the undoubted presence of man in this country during the Pleistocene period.

Dr. O. P. Hay vouched for the authenticity of this discovery, even though anthropologists are wont to question the association of the human remains with the true Pleistocene forms. He considered the fauna as of early Pleistocene age and cited evidence for this view. Doctor Matthew observed that he regarded the opinions of expert collectors of fossil vertebrates as to the validity of this discovery as carrying great weight, more probably, than the stratigraphic data.

CAMPODUS AND EDESTUS REMAINS

BY C. R. EASTMAN

(*Abstract*)

The very peculiar dentition of a shark was exhibited, which, being coiled, resembled more the form of an ammonite, and would hardly be taken for a vertebrate specimen by the casual observer. The teeth of the modern shark also come in succession, but this primitive animal had a great battery or coil situated anteriorly in its mouth, which furnished a constant supply of dental armature.

BRONTOTHERIUM: A NEW MOUNT IN THE YALE MUSEUM

BY R. S. LULL

(*Abstract*)

This specimen, shown by lantern slides, recently mounted in the posture of the famous model by Charles R. Knight, is the holotype of *Brontops robustus* Marsh (*Brontotherium robustum* Marsh). It is a specimen in excellent preservation and one unusually complete, which lay in the Yale Museum, spread out on the shelves, since 1875. It is one of the largest and finest of the Titanotheres, but not the most extremely specialized.

BAROSAURUS: A GIGANTIC SAUROPOD DINOSAUR

BY R. S. LULL

(*Abstract*)

Barosaurus is one of the gigantic dinosaurs of which a large portion of the backbone is known. It resembles *Diplodocus*, which it rivals in size. The

specimen was found in 1898 by Doctor Wieland and it is hoped that more of it may be secured. The great size of the beast may be judged by the length of one cervical centrum, which measures about one meter; posteriorly the vertebræ are not so large relatively.

OSTRICH DINOSAUR STRUTHIOMIMUS AND A RESTUDY OF ORNITHOLESTES

BY H. F. OSBORN

(Abstract)

This paper, which has since been published in Bulletin American Museum of Natural History, volume XXXV, 1917, pages 733 to 771, was discussed, as follows: Mr. Granger added to the four theories of the adaptation and habits of the animal a fifth, that of egg-sucking, which may have some bearing on the extinction of the larger reptiles. Professor Lull questioned the theory of the browsing habit of the animal and also the one advanced relating to its speed adaptation.

SKELETON AND RESTORATION OF CAMARASAURUS

BY H. F. OSBORN AND C. C. MOOK

(Abstract)

In the discussion by Messrs. Lull, Hay, Barbour, and Franklin it was shown that the lizards and crocodiles, which we usually think of as crawlers, sometimes get up on their feet and walk in a recognized quadrupedal manner. From this it was argued that the dinosaurs at times walked like mammals, and, again, may have sprawled like a crocodile.

Doctor Barbour has observed that crocodiles may walk leisurely, bearing the whole weight on their feet; but if hurried they drop down and wriggle along, using the tail and limbs, just as in swimming.

SUCCESSION OF THE MIOCENE FAUNAS IN THE JOHN DAY REGION

BY J. C. MERRIAM, CHESTER STOCK, AND CLARENCE L. MOODY

(Abstract)

Doctor Merriam read the paper, which was a discussion of the problems of stratigraphy of this Oregon region. Some excellent photographs, stratigraphic columns, and faunal lists were shown by lantern slides. Professor Osborn directed attention to the great advance in exact stratigraphic and faunal work in the John Day region since the early reports of Marsh and Cope.

RESTORATIONS OF THREE PLEISTOCENE SKULLS FROM EUROPE

BY J. H. MC GREGOR

(Abstract)

Perhaps the most interesting paper was this discussion of the early types of man in Europe. Professor McGregor illustrated with casts both the original fossil skulls and his restorations. He pointed out the characteristic features of the Heidelberg and male and female Neanderthal skulls, and the known or inferred differences between these primitive men and *Homo sapiens.*

Professor Osborn remarked that these restorations are the finest ever made; they set a new standard and are a real contribution to the hypothetical knowledge of the Hominidæ. Doctor Merriam expressed great pleasure in hearing the paper and said that it was worth coming across the continent just to see the restorations. He deplored the lack of material which would show us something of the evolution of the foot in man. Doctor Merriam congratulated the author of the paper, hoping that the results of his work will soon be accessible in publications.

CLASSIFICATION AND PHYLOGENY OF THE REPTILIA

BY S. W. WILLISTON

(*Abstract*)

The paper, illustrated by lantern slides and presented by Doctor Gregory, is the result of thirty years of research. Only the novel phases of the subject were brought out in particular, and to these Doctor Gregory made some valuable criticisms and additions. Doctor Matthew characterized the paper as a contribution of high importance.

The following papers were read by title:

CORRELATION OF THE UPPER CRETACEOUS IN MONTANA AND ALBERTA

BY BARNUM BROWN

EOCENE FAUNAL HORIZONS OF THE NORTHERN SAN JUAN BASIN IN NEW MEXICO

BY WALTER GRANGER

STRATIGRAPHY AND FAUNAL HORIZONS OF THE HUERFANO BASIN, COLORADO

BY WALTER GRANGER

HOMOLOGIES OF THE BORDERS AND SURFACES OF THE SCAPULO-CORACOID IN REPTILES AND MAMMALS

BY W. K. GREGORY AND CHARLES L. CAMP

USE OF FOSSIL FISHES IN CORRELATING STRATA

BY E. B. BRANSON

ORGANIZATION OF THE VERTEBRATE PALEONTOLOGISTS

The chairman read communications from various members who were compelled to be absent, namely, Dr. Roy L. Moodie, Dr. Wm. J. Holland, Mr. O. A. Peterson, Prof. E. C. Case, Dr. George F. Eaton, and Dr. W. K. Gregory, giving their views on the status of the organization of the vertebrate paleontologists and making recommendations for the future. Among the members present, Professor Osborn, Professor Lull, and Doctor Merriam spoke regarding the same matters.

On a motion of Professor Lull, the chairman was directed to appoint a committee, including the Chair, to formulate and submit to the Council of the Society recommendations in conformity with the opinions expressed at the meeting. On motion by Mr. Barnum Brown, this committee was given full power to act in all matters respecting the reorganization of the section.

On motion by Professor Osborn, the meeting was adjourned.

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Elvira Wood, Museum of Comparative Zoology, Cambridge, Mass.
Wendell P. Woodring, Dept. of Geology, Johns Hopkins Univ., Baltimore, Md.

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E. Koken, died November 24, 1912.

MEMBERS DECEASED

Samuel Calvin, died April 17, 1911.
Orville A. Derby, died November 27, 1915.
William M. Fontaine, died April 30, 1913.
Theodore M. Gill, died September 25, 1914.
Robert H. Gordon, died May 10, 1910.
J. C. Hawver, died May 15, 1914.
C. S. Prosser, died September 11, 1916.

MEMBERS-ELECT

Joseph A. Cushman, Sharon, Mass.
Henry M. DuBois, University of Illinois, Urbana, Ill.
Carl O. Dunbar, Peabody Museum, New Haven, Conn.
Richard M. Field, Jamaica Plains, Mass.
John B. Reeside, Jr., U. S. Geological Survey, Washington, D. C.
Wilbur I. Robinson, Vassar College, Poughkeepsie, New York.
Clifton J. Sarle, University of Arizona, Tucson, Arizona.
Edward J. Whittaker, Geological Survey of Canada, Ottawa, Canada.

MINUTES OF THE SEVENTH ANNUAL MEETING OF THE PACIFIC COAST SECTION OF THE PALEONTOLOGICAL SOCIETY

BY CHESTER STOCK, *Secretary*

The seventh annual meeting of the Pacific Coast Section of the Paleontological Society was held at Stanford University April 29, 1916. The meeting was called to order by Dr. John C. Merriam at 10.30 o'clock, in room 334 of the Department of Geology.

ELECTION OF OFFICERS

The following officers were elected for the ensuing year:

President, CHARLES E. WEAVER, University of Washington.
Vice-President, JOHN P. BUWALDA, University of California.
Secretary-Treasurer, CHESTER STOCK, University of California.

GENERAL BUSINESS

It was moved and carried that the President and Secretary be designated as official representatives of the Society on the Affiliation Committee of the Pacific Division of the American Association for the Advancement of Science. It was moved and carried that the next regular meeting of the Society be held in the San Francisco Bay region at a time agreed on by the officers of the Society. It was moved and carried that the Executive Committee be empowered to arrange for a special meeting at San Diego, if such meeting is possible.

The following papers were then read:

TITLES AND ABSTRACTS OF PAPERS PRESENTED

REVIEW OF PROGRESS IN PALEONTOLOGIC RESEARCH IN THE PACIFIC COAST REGION

BY JOHN C. MERRIAM

(*Abstract*)

An outline of advances in the study of extinct faunas in the area west of the Wasatch Range. Brief discussion of the most significant paleontologic problems touched by research in this area.

AN APALACHICOLA FAUNA FROM LOWER CALIFORNIA

BY RALPH ARNOLD AND BRUCE L. CLARK

(*Abstract*)

A collection of marine invertebrate fossils from near Magdalena, Lower California, was placed in the hands of the writers for determination by Arnold

Heim. Doctor Heim has recently completed a study of the geology of a portion of Lower California. Certain of the species, which come from beds described by him as *Purissima nueva* formation, are common to the Apalachicola horizon at a number of localities around the Caribbean Sea. Some of these species are *Pecten condylomatus* Dall, *Pecten oxygonum optimum* Brown and Pilsbry, *Rœta gibbosa* Gabb, *Mactra dariensis* Dall, *Turritella tristis* Brown. *Pecten condylonatus* is found in the Chattahoochee and Chipola beds of Florida and, according to Dr. R. E. Dickerson, is present also in the Tuxpan beds of Mexico. *Pecten oxygonum optimum* is common in the Gatun beds at Panama. *Racta gibbosa* was described from the Peruvian Tertiary and is also found, according to Doctor Dickerson, in the Miocene of the United States of Colombia, the fauna of which is considered by him to be a phase of the Gatun fauna. *Mactra dariensis* is found in the Gatun beds. *Turritella tristis* was described from the Miocene of Costa Rica.

The recognition of this fauna in Lower California is important in that it apparently indicates a direct connection between the Pacific and Atlantic oceans somewhere in the region of Central America during the Apalachicola period of deposition.

TERTIARY MOLLUSKS AND ECHINODERMS FROM THE VICINITY OF TUXPAN, MEXICO

BY R. E. DICKERSON AND W. S. W. KEW

(*Abstract*)

An interesting fauna has been collected recently by Prof. E. T. Dumble and Prof. W. F. Cummins from the Tertiary of the Gulf coast of Mexico. In this collection are several echinoderms which were described by Cotteau from formations of the islands of Cuba, Anguilla, and Saint Bartholomew. These were assigned to the Eocene by P. T. Cleve.

The echinoderm fauna was collected from seventeen localities north and south of Tuxpan. Of the fourteen forms found, *Clypeaster cubensis* Cotteau, of the Cuban Miocene, is most common. It is associated with *Agassizia clevei* Cotteau, from Saint Bartholomew, and *Macropneustes antillarum* Cotteau, from questionable Eocene of Saint Bartholomew and Cuba. Associated with the Antillean species are *Schizaster scherzeri* Gabb and Horn, from the Costa Rican Miocene; *Lovenia*, new species; *Clypeaster*, cf. *rogersi* (Morton); *Scutella*, new species; *Metalia*, new species. These forms are associated with *Pecten condylomatus* Dall, of the Chipola horizon of Florida; *Pecten oxygonum optimum* Brown and Pilsbry, *Pecten gatunensis* Toula, *Pecten levicostatus* Toula, *Clementia dariana* Conrad, *Turritella altalira* Conrad, *Malea ringens* Swainson, of the Gatun beds; *Ficus mississippiensis* Conrad, of the Vicksburg and Bowden horizons; *Conus interstinctus* Guppy, of the Bowden beds; *Hemipristis serra* Agassiz, of the Maryland and the California Miocene, and several other species which are characteristic of the Gatun beds. The fauna, as a whole, is littoral and is apparently an inshore facies of the Bowden and Chattahoochee horizons.

The fauna submitted by Professor Dumble and Professor Cummins suggests that certain so-called Eocene beds of Cuba, Anguilla, and Saint Bartholomew

which yielded *Agassazia clevei* Cotteau may be a stage of the Bowden (Miocene) of Jamaica. The presence of certain forms which are reported from Costa Rica and Panama show that an intimate relation exists also with these Tertiary horizons.

STRATIGRAPHY AND PALEONTOLOGY OF THE SALINAS AND MONTEREY QUADRANGLES, CALIFORNIA

BY H. J. HAWLEY

(*Abstract*)

The Salinas and Monterey quadrangles cover the northern part of Monterey County, California, and include the northern termination of the Santa Lucia Range, a small part of the broad alluvial plain of the Salinas Valley, and a small part of the western slope of the Gabilan Range.

The basement complex of gneisses, schists, granite, and crystalline limestone, on which all of the younger sedimentary formations were deposited after a long period of erosion, is of doubtful age.

The oldest sedimentary rocks exposed within these quadrangles are a series named by Lawson the "Carmelo Series," consisting of 1,320 feet of conglomerate interbedded with blue and brown sandstones and clay shales. These strata are unfossiliferous and their age placed as Chico because of the marked lithological resemblance to the Chico of the Santa Cruz quadrangle. Their relation to the Monterey shale is masked by intrusion of lava and by the overlying mantle of Paso Robles.

The oldest definitely known sedimentary formation is the Temblor sandstone, made up of 2,300 feet of red, blue, and green concretionary sandstone, which contains numerous forms of *Pecten andersoni*, *Turritella ocoyana*, and *Agasoma barkerianum*. Conformably overlying this sandstone is the typical siliceous diatomaceous Monterey shale, with a thickness of 3,500 feet. In the Corral de Tierra this shale is represented by a near-shore sandy phase. Many well preserved forms of *Arca montereyana*, *Pecten discus*, *Yoldia impressa*, and *Pecten peckhami* characterize this horizon. The Santa Margarita formation, of a thickness of 1,400 feet of white, coarse calcareous sandstone, with lenses of siliceous limestone and brown micaceous sandstones, overlies the Monterey shale with no angular unconformity, but the presence of pholas borings indicate a time lapse. From these sandstones specimens of *Pecten estrellanus* and *Ostrea titan* were collected in great number. This upper micaceous sandstone is conformable with the overlying Paso Robles formation. This unfossiliferous formation was correlated with the Paso Robles of the San Luis quadrangle and the Salinas Valley on a purely lithologic basis. It consists of a very coarse, unsorted, loosely consolidated conglomerate in the steep mountains, passing gradually into a light brown to yellow fine-grained concretionary sandstone in the northern part of the Monterey quadrangle.

A flow of basic lava exposed in small patches about the mouth of the Carmel River poured out after the deposition of the Monterey and before the Paso Robles was laid down.

SUPPLEMENTARY DATA BEARING ON THE COMPOSITION AND AGE OF THE THOUSAND CREEK PLIOCENE FAUNA

BY JOHN C. MERRIAM, CHESTER STOCK, AND E. M. BUTTERWORTH

(*Abstract*)

The material obtained by a recent expedition to the Thousand Creek Pliocene deposits of Nevada had made possible a more minute analysis of the faunal relations of these beds.

CLIMATIC RELATIONS OF THE TERTIARY OF THE WEST COAST

BY JAMES PERRIN SMITH

(*Abstract*)

An exhibit was made of columnar sections from Eocene to Recent in five climatic zones from Panama to Alaska, showing the actual specimens characteristic of the climatic zones, as well as of the geologic horizons. A chart was also exhibited, showing the stratigraphic relationships of the faunas and the shifting of the isotherms in geologic time.

RECENT ADDITIONS TO OUR KNOWLEDGE OF CALIFORNIA CENOZOIC ECHINOIDS

BY W. S. W. KEW

(*Abstract*)

The large collections of California echinoids acquired during the past few years permit a more accurate determination of the geologic range of genera and species. The number of species is greatly increased and the status of the known forms more satisfactorily determined. Prior to the year 1913 thirty-one species of echinoids and stelleroids were described; since then twenty-one additional forms have been added to this list. Undescribed forms in the collections of California institutions will increase the number at least 60 per cent. The geologic range of some of the more important genera on the Pacific coast, including also the undescribed species, is as follows: *Cidaris*, Eocene, with the exception of one species in the Oligocene and one in the Pliocene; *Strongylocentrotus*, Pleistocene and Recent; *Scutella*, mainly throughout the Miocene, with fragmentary specimens from the Eocene; *Dendraster*, Pliocene, with the exception of *Dendraster excentricus*, which is living, and *Astrodapsis*, confined to the Upper Miocene and Lower Pliocene.

STRUCTURE OF THE PES IN MYLODON HARLANI AND ITS BEARING ON THE PROBLEM OF SUPPOSED HUMAN ORIGIN OF FOOTPRINTS OCCURRING NEAR CARSON, NEVADA

BY CHESTER STOCK

(*Abstract*)

In the restoration of the pes of *Mylodon harlani*, based on the material from Rancho La Brea, the second and third phalanges of digit 3 are identified with

the corresponding phalanges of digit 2, manus of *M. robustus*, as interpreted by Owen. In Owen's reconstruction of *M. robustus* the second and third phalanges of digit 2, manus, have undoubtedly been interchanged with the corresponding phalanges of digit 3, pes.

In 1882 H. W. Harkness described what he believed to be imprints of a sandaled human foot occurring in Pleistocene strata near Carson, Nevada. These footprints were exposed, together with those of other animals, in the stone quarries of the Carson State Prison yard. Shortly following this description Joseph Le Conte pointed out obvious objections to the theory of the human origin of these footprints, namely, the large size of the individual imprint and the span of the straddle. He suggested that the imprints were made by a large quadruped, most probably a ground-sloth. The latter view was entertained also by O. C. Marsh, who made comparison between the imprint and the outlines of the pes of *Mylodon*.

An interesting verification of the views of Le Conte and Marsh is suggested by the restoration of the pes of *Mylodon harlani* from Rancho La Brea. The posterior foot of this species corresponds very closely in size and shape with the imprints found in the Pleistocene of Carson City, Nevada.

TERTIARY NASSIDÆ OF THE WEST COAST OF AMERICA

BY STANLEY C. HEROLD

(*Abstract*)

A review of West Coast Tertiary species of the family Nassidæ (Alectrionidæ), ranging from Puget Sound to Ecuador, prepared in conjunction with a discussion of the living Nassidæ from the same region by Mrs. Ida Oldroyd. Their synonymy and stratigraphic range is established, certain forms are differentiated and specifically named, and new species are described. An attempt is made to determine their phylogenetic relationships, as evidenced by stratigraphic and geographic distribution and faunal variations of the individual species.

ASTORIA SERIES (OLIGOCENE) IN THE REGION OF MOUNT DIABLO, MIDDLE CALIFORNIA

BY BRUCE L. CLARKE

(*Abstract*)

The formations in the region of Mount Diablo, here referred to the Oligocene, until comparatively recently were included in the Lower Miocene, being correlated with the Temblor (*Turritella ocoyana* zone), as described by F. M. Anderson from the region of the Temblor Mountains and near Kern River, in the vicinity of Bakersfield, California. The beds of this horizon, as mapped in different parts of the State by the United States Geological Survey, are referred to under the name of Vaqueros, which is the equivalent of the Monterey group of Prof. A. C. Lawson.

The first announcement of the separation of these Oligocene beds from the Miocene was made by the writer in a short paper entitled "Occurrence of

Oligocene in middle California."[1] Briefly stated, the conclusions were as follows: At the base of the Monterey group, in certain localities to the west of Mount Diablo in the Concord quadrangle, as described and mapped in the San Francisco Folio,[2] a portion of the lower sandstones, designated as the Sobrante formation, contains a very distinct fauna from that found in the sandstones and shales immediately above; the paleontologic and stratigraphic evidence indicates that these lower beds belong to a distinct period of deposition, there being a marked stratigraphic, as well as a faunal, break between the two. The name *Agasoma gravidum* zone was applied to the lower beds; the fauna in the beds immediately above the break was referred to the *Arca montereyana* zone. The fauna of the *Agasoma gravidum* zone was correlated with that of certain beds in Washington and Oregon, which beds have been referred to the Oligocene by different writers.

Since the publication of this paper more extensive field-work has been done and the writer has been able to get much better acquainted with the Oligocene fauna of Oregon, Washington, and Vancouver Island. The term Astoria series, as used here, was first applied by Arnold and Hannibal as a general name for the Oligocene of the west coast in their paper entitled "The marine Tertiary stratigraphy of the North Pacific coast."[3] This name is synonymous with the term Clallam formation, as used by Prof. C. E. Weaver in his recent paper entitled "Tertiary faunal horizons of western Washington."[4]

Beds in the region of Mount Diablo, referable to the Astoria series, are found in two general sections—one to the west and one to the north of the mountain. These two sections are very different, both lithologically and faunally. The beds to the west of the mountain in the Concord quadrangle have a maximum thickness of only a little more than 500 feet. To the west and south of the Concord quadrangle they disappear and the beds of the *Arca montereyana* zone (Monterey) rest directly on the Tejon (Upper Eocene) or older formations. The Oligocene formations north of the mountain (Mount Diablo quadrangle) have a maximum thickness of over 3,500 feet. They are more heterogeneous than those found in the Concord quadrangle and contain at least one disconformity; they are overlain unconformably by the San Pablo group, the Monterey group being absent. The fauna obtained from these beds on the north side of the mountain and on which the determination of their age is based came from near the top of the series. At the present time something like forty marine invertebrate species have been found in the Oligocene beds to the north of Mount Diablo, while over one hundred species have been obtained from the beds to the west of the mountain.

The fauna obtained from the Astoria series in the region of Mount Diablo, considered as a whole, appears to be more closely related to the Lower Oligocene of Washington and Oregon than to the Upper, a number of identical or very closely related forms being common to these beds and the beds in Washington assigned by Weaver to the Lower Oligocene, the "Lincoln horizon" (*Molopophorus lincolnensis* zone), which in part is the equivalent of the San

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[1] B. L. Clarke: Univ. Calif. Publ., Dept. Geol., vol. 9, no. 2, 1915, pp. 19-21.

[2] A. C. Lawson: U. S. Geol. Surv. Atlas, San Francisco Folio (no. 193), 1914.

[3] Ralph Arnold and Harold Hannibal: Proc. Amer. Phil. Soc., vol. lii, 1913, pp. 576-585.

[4] C. E. Weaver: Univ. Wash. Publ. in Geol., vol. i, no. 1, 1916, p. 4.

Lorenzo formation of Arnold and Hannibal. Some of these common forms are fairly highly ornamented gastropods, and it might be expected that they would have a rather limited geologic range. It should be remembered, however, that the work of describing the faunas of the Oligocene has only begun and the range of many of the described species has not been established for a certainty. For this reason the writer hesitates to say that the *Agasoma gravidum* beds are certainly as old as the Lincoln beds of Weaver, but there seems to be no doubt that they belong to the same general period of deposition, if not to the same faunal horizon. The San Lorenzo formation in the region of the Santa Cruz Mountains, described and referred to the Oligocene by Dr. Ralph Arnold, belongs to this same period, as do also the Kreyenhagen shales recently described by Robert Anderson and Robert W. Pack and referred tentatively to the Oligocene.[5]

Sufficient faunal evidence has now been obtained to show that these shales belong to the Astoria series. The Astoria series is also known to be represented by beds at the south end of the San Joaquin Valley in the San Emigdeo Hills. In this general locality the Oligocene strata are separated from those of the Miocene (Monterey group) by volcanics of considerable thickness.

FAUNA OF THE ETCHEGOIN PLIOCENE OF MIDDLE CALIFORNIA

BY J. O. NOMLAND

(*Abstract*)

Results of studies on the Etchegoin Pliocene in the region of Coalinga, California, may be summarized as follows:

1. Pliocene sediments have accumulated to the thickness of over 10,000 feet in this area under shallow marine or terrestrial conditions.
2. While marine accumulation prevailed the floor of the basin of deposition was raised locally several times above sealevel; after terrestrial conditions became predominant brief periods of marine deposition occurred.
3. In post-Pliocene time diastrophic movements of great magnitude occurred in the Coalinga region.
4. The strata above the Santa Margarita (?) and below the Tulare belong to one period of deposition.
5. The Santa Margarita-San Pablo fauna is distinctly different from that of the Etchegoin.
6. As shown by the invertebrate and vertebrate faunas, the whole Etchegoin is of Pliocene age.
7. An unconformity in the lower part of the section heretofore grouped with the Etchegoin southeast of Coalinga is probably the line of division separating the Etchegoin from the Santa Margarita (?)
8. An unconformity above the "Glycimeris zone" in the Etchegoin north of Coalinga is probably only of local importance.
9. Four distinct faunal zones have been recognized in the Etchegoin formation.

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[5] Robert Anderson and R. W. Pack: Geology and oil resources of the west border of the San Joaquin Valley north of Coalinga, California. Bull. U. S. Geol. Survey, no. 603, 1915, pp. 77-78.

10. The Lower Etchegoin is most closely related to the Lower Fernando Pliocene near Newhall, while the Upper Etchegoin is most closely related to the Lower Pliocene beds at Sargent.

FAUNA OF THE PINOLE TUFF

BY JOHN C. MERRIAM AND CHESTER STOCK

(*Abstract*)

The fauna of the Pinole tuff has been known by a small number of invertebrate forms from the type locality near Rodeo Station, on San Pablo Bay, in middle California. Vertebrate remains discovered in a section of loose gravels and tuffs near the town of Pinole, on San Pablo Bay, have recently been shown to represent the Pinole Tuff stage. Recent collections from the Pinole locality have added to the vertebrate fauna several genera not previously known at this horizon and much better material of several forms represented at the type locality, The collections now available make possible a much more satisfactory correlation than that heretofore proposed.

LOWER AND MIDDLE CAMBRIAN FAUNAS OF THE MOHAVE DESERT

BY C. W. CLARK

(*Abstract*)

Lower and Middle Cambrian sedimentary rocks occur on the Mohave desert near Cadiz, California. The Lower Cambrian rests here on the Precambrian granites and schists. Late Paleozoic, marbleized limestone, probably Carboniferous in age, rests conformably on the Middle Cambrian. The general distribution of these formations is shown in the Guide Book to Geology, etcetera, Santa Fe Railroad. All the localities of sedimentary rocks noted in the Guide Book as occurring near Cadiz were visited, excepting those in the Providence Range, but fossils were obtained only from the Bristol Mountains (Iron Mountains).

The Lower Cambrian is represented by the Olenellus fauna, to which one new genus and three new species of trilobites have been added. Several specimens of *Bathyuriscus* mark the Middle Cambrian. A few species of Carboniferous fossils were found near the top of the marbleized limestone, which is the uppermost formation of the sedimentary series in this region.

ANCIENT PANAMA STRAITS

BY ROY E. DICKERSON

(*Abstract*)

According to Stanton, the Pacific and Texas Cretaceous have no species in common, and although he recognizes the presence of an Upper Cretaceous series containing a Pacific fauna resting on a Lower Cretaceous, Comanchian stage at Catorce, he states that in no place in the entire region has a commingling of Upper Cretaceous faunas of these two provinces been found.

Beds of Eocene age containing several species common to the Tejon of California occur along the Mexican Gulf border. White limestones in the Isthmus

of Tehuantepec may be of Eocene age. The faunal relationships between the Mexican Coastal Plain and the Tejon of California indicate that there were straits which were probably situated in the Isthmus of Tehuantepec during Upper Eocene time. The lack of a close relationship between the faunas of the Martinez-Eocene stage and the Midway indicates the opposite conclusion. The evidence concerning the Lower Oligocene or Vicksburg stage is quite deficient and it is impossible to determine any connections at this time.

Spencer postulates Pliocene canals through the Isthmus of Tehuantepec. Bose and Toula, who have studied the Isthmus of Tehuantepec, disagree entirely with Spencer's geologic data, and state that it is impossible to trace marine terraces across the Isthmus, although they recognize the presence of stream-laid deposits resting on rocks bearing a Bowden fauna. The faunal evidence along the various lines discussed below in no manner indicates any recent connections.

Faunal relations of the living mollusks, fishes, echinoderms, and corals from the Panamic and Caribbean provinces indicate that no connection existed between the Atlantic and Pacific during the Pliocene or Pleistocene. A study of the mammals of North and South America demonstrates that a barrier was present during the Miocene. The recent Panamic marine invertebrate fauna is related to that of the Bowden horizon of Jamaica, and straits probably existed at various times during the deposition of the Bowden beds.

According to Hill, during Cretaceous time the major islands of the Antilles were started on the crests of oceanic volcanoes. These land-masses thus built up were submerged in part and the sediments deposited from their erosion contain a fauna of Upper Cretaceous age. At the end of Cretaceous time these strata were folded along a northwest-southeast axis. In late Eocene and early Oligocene time a profound regional subsidence occurred, during which all but the highest tips of the Antilles were covered by the waters of the Caribbean. This subsidence was followed by an uplift in Oligocene time, during which great orogenic movements along east-west axes took place. This was the stage, if at all, of an Antillean continent. Possibly many of the larger islands were connected at this time, and the southern portion of Florida may have been linked with this large Antillean island. This event was succeeded by another great submergence, and portions of Mexico and Central America, as well as the major portions of the Antilles, were largely covered with oceanic waters—the Bowden stage.

According to the work of Scott and Matthew in the study of recent and fossil mammals, any connection of the mainland with the Antilles is very unlikely. The species of small sloth found in the Pleistocene beds of Cuba sprang from a single form which may have emigrated there by way of a raft. Scott shows that during Miocene time the mammalian fauna of North and South America were entirely distinct. These facts indicate that a period of wide-spread submergence occurred during the Miocene, and on this account the beds bearing the Bowden fauna might well represent this era of subsidence.

Recently a fauna collected from the vicinity of Magdalena Bay, Lower California, was submitted to Dr. Ralph Arnold and Dr. B. L. Clark for determination. This fauna contains *Pecten condylomatus* Dall, of the Chipola horizon of Florida and the Tuxpan beds of Mexico; *Pecten oxygomum optimum* Brown and Pilsbry, of the Gatun beds, Panama; *Rœta gibbosa* Gabb, of the Peruvian

Tertiary and the Miocene of the United States of Colombia—a phase of the Bowden fauna; *Mactra dariensis* Dall, of the Gatun beds; *Turritella tristis* Brown and Pilsbry, of the Costa Rica Miocene. The rest of this fauna contains casts of forms which represent typical Bowden genera. The fauna, beyond doubt, is some phase of the Bowden or associated horizon, and straits connecting the Atlantic and Pacific at this stage of the Tertiary is thus conclusively proven.

Doctor Dall has compared the Bowden fauna to that of Bordeaux and the Aquitanian. Guppy has also compared the fauna to the Dax Miocene and the Bordeaux. The age of the Aquitanian has not yet been definitely settled. De Lapparent places it as Lower Miocene and the Stampian and Tongrian in the Oligocene. Most of the faunal comparisons made by Guppy indicate the same stage, but the Antillean fauna may have developed by convergent evolution from an earlier somewhat cosmopolitan fauna of Upper Eocene age, or we may be dealing with a case of parallel evolution. Most of the European forms identified in the Antilles—the corals, for example—by early investigators have been rejected by the investigators of today. Thus Vaughan rejects all Duncan's European species as occurring in the Antilles. It seems that an Atlantis is quite unnecessary to account for the faunal relationship between the West Indies and the Miocene of Europe. According to Hill, *Orbitoides mantelli*, a characteristic Oligocene form, does not occur in the Bowden beds. Thus the best evidence for Oligocene age has disappeared or is rendered doubtful. Hill states the exact date of this fauna as follows: "In my opinion, it was during late Miocene and Pliocene time, beginning with the Bowden epoch of the Jamaican sequence. Doctor Dall holds that the age of the Bowden beds is late Oligocene. It is my opinion that the stratigraphic relations of these beds in Jamaica indicate a later age. Deferring to Dall's opinion, I have tentatively accepted his conclusions, however, until more field-work can be done. Thus diastrophism indicates a Miocene age for Bowden fauna, as shown above. The lack of relationship between Miocene mammalian faunas of North and South America indicates a wide-spread submergence at this time. The Oligocene of the Pacific contains no forms common to the Bowden fauna. All investigators have recognized a number of living species in this fauna—Gabb, 30 to 40 per cent; Moore, 8 to 9 per cent; Guppy, 20 per cent; Brown and Pilsbry, about 5 per cent."

The following is a summary of the conclusions reached:

(1) No connections between Atlantic and Pacific oceans in the vicinity of Central America occurred during Cretaceous time.

(2) The Panama and Tehuantepec portals were closed during the Lower Eocene, but were open during the Middle or Upper Eocene.

(3) Straits existed during that portion of the Tertiary which is characteristically represented by the Bowden horizon.

(4) The Bowden fauna was probably evolved in part from a somewhat cosmopolitan Middle or Upper Eocene fauna and in part from Miocene or Oligocene faunas of provincial Pacific origin.

(5) The diastrophic record, the relations of Miocene mammalia of North and South America, the stage of evolution of the Bowden fauna in terms of the Recent, and the presence of several living species indicate that the age of the Bowden is probably Miocene and not Oligocene of some authors.

OCCURRENCE OF NOTHROTHERIUM IN PLEISTOCENE CAVE DEPOSITS OF CALIFORNIA

BY CHESTER STOCK

(*Abstract*)

The ground-sloth Nothrotherium was originally described from material found in cave deposits of Brazil. A recent study of the ground-sloths from the Pleistocene deposit of Samwel Cave, Shasta County, California, has shown the presence of Nothrotherium associated with *Megalonyx*. *Nothrotherium* is known also from Potter Creek Cave, in Shasta County, and from Hawver Cave, in Eldorado County. The range of this ground-sloth in North America is apparently more restricted than that of *Mylodon* or *Megalonyx*. Except for its occurrence in California, the genus is known only from the Pleistocene of Texas, where it has recently been recognized by O. P. Hay.

CRETACEOUS AND TERTIARY HORIZONS IN THE MARYSVILLE BUTTES

BY ROY E. DICKERSON

(*Abstract*)

Recent investigations at Marysville Buttes, an ancient volcano of the Sacramento Valley, have revealed the presence of the Knoxville and Chico groups. The areas mapped as Ione in the Marysville folio are composed, in part at least, of four different terrains—the Knoxville, the Chico, the Tejon (*Siphonalia sutterensis* zone), and the Sutter formation. The last is a land-laid deposit consisting largely of rhyolitic debris of the first volcanic eruption. These terrains were in turn disturbed by an andesitic intrusion, thrown on edge and faulted in places.

The sequence of events which gave us the Marysville Buttes in their present form appears to be as follows:

(1) The accumulation of limestones and shales of Knoxville age in a great geosyncline, the eastern border of which was probably in the vicinity of the present site of the Marysville Buttes.

(2) A recession of the sea from the eastern border of the geosyncline during the deposition of the Horsetown horizon.

(3) The lowering of the continental margin and the deposition of Chico-Cretaceous strata by a transgressing sea from the west.

(4) A great time interval during which this site was land.

(5) Submergence at the end of Tejon time, which resulted in the deposition on the outer edge of the continental shelf of Eocene strata composed of foraminiferal shales, the deep-water equivalents of the inshore Ione of the Sierran foothills.

(6) Uplift.

(7) An intrusion of rhyolite and consequent upturning and faulting of Cretaceous and Eocene strata and outpouring of rhyolitic flows and ash deposits (the Sutter formation) on these faulted and folded sedimentaries.

(8) A period of erosion during which a large portion of the Sutter formation was removed.

(9) An intrusion into these older formations mentioned above and outpouring of andesitic materials from a great central volcano.

(10) A long erosion interval during which short streams consequent on the lava slope cut through the andesitic lava into the softer underlying deposits. Of these deposits the softest is the Sutter. The pass between the towns of West Butte and Sutter City was cut in this material. The "secondary craters" described in the Marysville Buttes Folio appear to be erosion valleys formed in the Sutter formation by subsequent tributaries of consequent streams.

In conclusion, there does not appear to be any formation in the Marysville Buttes except the Tejon Eocene strata which could possibly be the equivalent of the Ione of the Sierran foothills. It has been shown above that these Eocene strata are the offshore equivalents of the inshore Ione.

FAUNA OF THE FERNANDO FORMATION OF LOS ANGELES, CALIFORNIA

BY CLARENCE L. MOODY

(Abstract)

An excavation near the center of the city of Los Angeles in 1913 brought to view a fossiliferous stratum about 15 feet from the surface which yielded a large marine molluscan fauna. Collections were made by Mr. J. Z. Gilbert, of the Los Angeles High School, and the material was intrusted to the University of California for study.

The fauna contains a number of forms of boreal habitat, while not a few subtropical species are represented. About 15 per cent of the fauna is extinct. Restricted Pliocene species are *Thracia trapezoides* Conrad, *Turris mercedensis* Martin, *Natica orbicularis* Nomland, *Pecten healeyi* Arnold, *Pecten opuntia* Dall, and *Pecten bellus* Conrad, beside ten species regarded as new.

The fauna has affinities with the Middle Fernando of Santa Clara Valley and with the San Diego Pliocene of San Diego and San Pedro. It seems to represent a higher zone in the Pliocene Fernando than has heretofore been recognized.

At the conclusion of the reading of the papers the meeting adjourned and the members of the Paleontological Society attended the dinner of the Le Conte Club at the Stanford Union.

Register of Members and Visitors at Stanford Meeting, 1916

A. L. Barrows
E. M. Butterworth
J. P. Buwalda
E. B. Camper
B. L. Clark
C. W. Clark
N. C. Cornwell
E. F. Davis
R. E. Dickerson
A. S. Eakle
F. Mc. Hamilton
H. J. Hawley
S. C. Herold
W. S. W. Kew
A. C. Lawson
R. P. McLaughlin
J. C. Merriam
C. L. Moody
J. O. Nomland
Ida Oldroyd
J. P. Smith
C. Stock
C. F. Tolman, Jr.
H. W. Turner

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 28, PP. 235-248 MARCH 31, 1917

THE PHILOSOPHY OF GEOLOGY AND THE ORDER OF THE STATE[1]

PRESIDENTIAL ADDRESS BY JOHN M. CLARKE

(Read before the Society December 28, 1916)

Once each year we come together to renew our strength in unison, like Antæus, by touching the earth.

I am conscious of taking some degree of liberty in departing from the usual form of this established function—the annual address. It would gratify me and might in some measure have diverted or persuaded you, if this occasion were given to the illumination of some specific technical theme. But the spirit of the hour seems to impel me rather to read from my experience and observation, or at least to portray as I see it, some part of the obligation of the State to our science and the responsibility of this science to the State.

The occasion is perhaps opportune, not so much in this place of meeting which happens to be the seat of government of but one of the many States here represented, and in the presence of members from two great federated governments; but essentially because, for the sake of all parties of interest, we must recognize more clearly the civic element in geological science and insist more pertinaciously on the immediate as well as the ultimate dependence of a State, if organized to endure, on the demonstrated laws of this science.

I wish I might extend to my colleagues among the official geologists of many States an assurance that this address is to be devoted to some added demonstration of the obligation of the State to exploit to the utmost its geological resources, for the sake of the commercial interests of its community, but such public arguments are now superfluous. It is a primary impulse and almost elemental instinct in the State to develop the commercial assets of its rocks. The appeal is so direct, so simple, so imperative that no State can afford to ignore a well directed official effort to increase thus the general well-being and comfort of the commonwealth. The broad proposition is not debatable; the proposition in detail has always been debatable and debated. Too often and too much in representative public opinion is the existence of the official geological organization justified by certain perfectly obvious considerations which subtend a large angle in the public consciousness. Gold and silver, iron and coal, petroleum and natural gas, and terms like these are made too often to set forth a reasonable vindication of official geology. But you and I may well insist that such factors as these reckoned in terms of the wealth of the State are not the justification of official geological research. We may as well draw back the veil—private enterprise will pretty effectively take care of such things as these without much help from us. Against such factors which we may term the obvious sources of wealth must be weighed the more recondite products which have seldom entered into the estimate of the law-making body or the public knowledge.

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[1] Manuscript received by the Secretary of the Geological Society March 17, 1917.

It is in these that many of our States are richest, not in those obvious factors. In a State like this, which I cite not for comparison but for illustration, the unexploited iron ore would seem to be well over a billion tons, while the actual value of the annual product of iron is not more than one-tenth that of the annual output from thirty or more different mineral products; and we can not even begin to estimate for our State the vast reserves in products undeveloped or conceive the now unknown applications to industry and the arts which our commonest geological compounds are competent to supply in response to the demands of the State.

I can see in such a State or in a union of States and governments as ours, the demand for every human need, today actual and tomorrow possible, which is in any way dependent on the rocks of the earth, fully met here without reliance on any outside source; and it is of eminent importance that the State take counsel with itself to magnify such independence, at the sacrifice of its commercial ease, for dependence in commerce means no less than does dependence in the scheme of nature, that is, degeneration or stagnation.

I counsel, therefore, you who are official servants of the State, to urge, within your power, on the State this primary obligation: to take from no other what it can itself as well produce from its own stores. Insist, as the right is in you, that the State shall take account of the knowledge you possess for the full but conservative development of its own resources, and neglect no occasion to enforce the claims of the man who knows best, to precedence in these councils of the States.

A State geologist is the official adviser of his government in this matter of development of potentialities for good in the wealth of the rocks, but every geologist, official or personal, should so far keep the public welfare in his eye as to be ready for initiation and cooperation in a service of so high a quality.

I would not seem to profane my high office by stating in this presence the elemental conceptions of the science, but it is most imperative that I here, and you elsewhere, shall be lucid, exact and comprehensive in setting forth its claims, namely and briefly: that there is no substantial conception of property apart from the products of the rocks, the soils, the mines, the water, the air—and these in all their functions are geological factors; that there is no correct understanding of the meaning of human life, individually or in its complex community relations, if we stand with our backs to the great panorama of events which have builded the earth and the trains of life which have moved over it from the dawn of its history. It is most essential that every State should, above all things, comprehend these facts.

The current of my thoughts is toward the well established principles of geology which have constituted the State; not the State as a geographical section of the earth, and not just now those principles which have laid its material foundations, builded its rocks, formed its veins and beds of ore, made its soil, established the sources of wealth as expressed in terms of human market; but unavoidably I turn to those principles which illumine the trail of humanity and have given it direction. My time has been long enough to ripen some of the green fruit of experience and enforce some deep-seated lessons. In the light of this experience and these associations there is no escape from the earnest conviction that the things of supremest value to mankind, the refined essences of the earth, lie in its records of the life which has gone before us. As the emergence of what we call the living, quoting Professor Chamberlin, is the transcendent event in the history of the earth, there is certainly no other fact in the presence of humanity so vital as that, and the vast procession of the ages with the key it holds to our present state and future hopes. Need I say to this audience what I would wish to say to a wider: We are passing, we have stopped only to see the march of life and play our small part in the tremendous and endless pageant, happy indeed if, endowed with powers of divination, the rays of truth have dawned on us from out the past, to light the imagination on toward better things.

To what extent, then, are we fortified by the evidence of the past career of life in reading its oracle for our present guidance? This inquiry sets plainly before us, first, the paramount question as to the oft alleged and too often magnified imperfections of the record of life on the earth.

In many, probably in most, expositions of the science of geology and paleontology, prepared for the use of students and general readers, the so-called imperfections in the record of past life are brought out with a vivid intensity. These expositions are, I think, in large part due to a more or less unconsciously apologetic attitude on the part of the authors, as though they were in some way, being apostles of the science, likely to be held to account for any overstatement of its claims; and these attorneys in bankruptcy are not inaptly, to my mind, comparable to buyers of ancient but damaged rugs—torn, raveled, worn bare of their patterns: ostentatiously declaring their defects while overlooking the beauty, the symbolism, the perfection of the design, seen clear through all the ravages made by the wear of time.

I find myself out of sympathy with such deprecating portraitures. Neither my experience nor my philosophy finds support for pessimistic conceptions of the ultimate hope of completing our tapestries from the patterns we know and the threads we are yet to pick up. For a few years, as we reckon human history, we have scratched with our hammers some surface exposures of the tablets of the law in parts of the earth most easily accessible to us, and the occasional explorer into remoter parts has gathered the life records in haphazard way, here a few pounds weight, there a few tons. Not one-fiftieth part of the exposed rocks of the earth has yet been closely scrutinized for these life records, and of the unexposed, but known, strata, practically none at all in the great total. This State of New York covers 47,000 square miles, two-thirds of which are underlaid by life records of the earth. This fossiliferous area is one-eighteen-hundredth part of the land area of this globe, about one-eleven-hundredth part of the exposed fossiliferous rocks. In this State the work of assembling the evidences of the life record has proceeded continuously in organized attack for eighty years. An eminent French geologist has intimated that there are few places of equal area in the world where the life record is so completely assembled—and yet every year brings new and necessary additions to our quiver. What shall we say of the other 1,099 equal areas of fossiliferous rocks on the earth? Many of them have indeed been studied with precision, but there remains and must remain for long years yet an overwhelming balance of the unknown. In the abundance and perfection of the life that is preserved in these rocks only the living seas themselves are comparable. I have estimated the number of individuals of a few of the species occurring in one insulated mass of marine Devonian strata known as the Percé Rock, a section which above the water line represents a sea deposit 300 feet thick, 1,300 feet long, and about 250 feet wide, and the figures for these few species run into the hundreds of millions of individuals—and yet the rock is not richly fossiliferous, in the customary use of that expression.

It seems to be my experience, too, that the most closely studied formations have already yielded up a large percentage of their actual fauna. For some well studied formations in limited areas the known fauna is, approximately speaking, a true and fairly full expression of the actual fauna. I can not of course pursue this matter here into its further details with its brilliant vistas already before us of learning the inchoate life of the primitive soils and impounded waters, but I think I shall venture to enter the lists on call, to contend that for plant and animal life alike the records of the rocks, where unaltered, are unimpeachable for adequate suggestiveness of the designs which the threads of life have woven. And when the imputation is too often made of imperfection through loss of anatomical detail, or the destruction of essential structures, compare by way of simple illustration compressed into the emergencies of this occasion the growth of knowledge of fossil anatomy within the fragment of the lifetime of one man. Fifty years ago all that was known of the ventral organization of the trilobite was a mere suggestion embedded in a nest of speculations; of its ontogeny a few discrete facts. So far has knowledge advanced that today we seem to know these animals in all their essential details and development; and if aught is left to become known of internal anatomy or ecology, the lessons of the past are the promise of the future. What was known of the Eurypterida fifty years ago was little but their outline and their grosser form. Today their ontogeny is understood almost from birth onward, their anatomy almost to ultimate details, their habits at least as well as those of vast numbers of living animals, their phylogeny as well as or better than the phylogeny of any living race subjected to this speculative treatment. Supplement these illustrations, which are nearest to me, with the scores of others known to you, and with the tremendous strides made in this same period of time among the extinct vertebrates, and within the realm of lost floras where sheaves of knowledge are piled higher with every year.

These are the theses I should wish to nail on the doors of our temples:

Nature makes for the individual. This truth is registered on the tablets of the earth; it lies also in human observation and in human experience. Its recognition is of paramount importance; its acceptance sweeps away cobwebs of vagrant hypotheses which befog the pages of writers on political and social economics.

In the progressive line of development, which in the present terminates in us, the procedure of nature has been one of only limited concern for the family and of tried out and abandoned experiment for social partnerships and the division of labor. To perfect the individual, inconceivable safeguards have been thrown about him. The individual is creation's unit, in terms of which all progress in life is to be reckoned. With unsparing hand she makes and wastes these units, both for her greater purposes and those which we may call her lesser ones. Units of purpose are wiped away to make place for units of other purpose. Yet the unit type remains; remains with its full seeding of possibilities, armored for its fight with double portions of food supply, of sense organs, of locomotive means, with an inexpressible superfluity of reproductive supply. Whether a given unit survive till its work be done or perish in the doing, it is the individual type that is at stake, it is against this individual type that all the powers outside it are imposing their obstacles.

This the geologist knows: There has been no cooperation in the historic development of the life in which we are directly concerned. We may not yet know the trend of many life lines for far in their history, but wherever such lines are best known, within the limitations of large natural divisions, those that run through from limit to limit and point the way both backward and ahead, and those other lines collateral to ours which have ended and determined fruitlessly—these all can be conceived in no other way than variant expressions of the individual. And in the history of human life is it aught else than the individual that has stood for the progress of mankind? Was it the barons at Runnymede, was it some bill of rights, some declaration of independence, some joint action of human agencies, that have been the crowns of our achievements? Or was it the Aristotle, the Plato, the Socrates, the Christ, a solitary Shakspeare, an incomparable Franklin, a rebellious Darwin, or the historic twenty individuals who have stood for the progress of the race?

I say this only for the purpose of saying, *per contra*, that the history of the excellent life (and by that I mean the line of life that is best perfecting its psychology), has shown the futility of attempts at progress through any other agency than the independent individual. This is so important a conclusion to every State taking cognizance of its dependence on natural laws that it is highly essential to consider nature's own alternatives to such individualistic effort, her own experiments in trying out other modes of ascending heavenward. For "individual liberty," said

President Butler, speaking before the Constitutional Convention of this State, "is the cornerstone of the free State." That is the decree which is written in burning letters on every mile-post of the course of life. "The perfection of the individual is the perfection of the race," says Professor Hoffman. "But," he adds, writing on the organization of the State, "the individual can have no rights or duties that conflict with the good of the whole"—a supplement for which it is exceedingly doubtful that any substantiation can be found in nature.

a It has been my environmental control to study and, I hope, to learn some of the lessons of life from their simplest and most easily legible expressions—a result that has come from living and laboring in a State built from the early waters with their undifferentiated expressions of life. The panorama of successive early worlds of life glows with the simple expressions of law which become more involved, supplemented and beclouded as the passing of the ages complicates the process of higher evolution, and produces expressions which, in terms of existing life alone, would be difficultly intelligible. The study of the meaning of existing life without the light of its vast history leads nowhere.

It is safe to say, I think, that living beings at the start, animated nature, whatever its composition, had an equal chance for progress and improvement. How soon that chance became forfeit we can not say, but it is obvious that life was not long begun and its greater stocks established when their courses throughout existence were set and determined. Nothing is more obvious in chronology than nature's deliberate failures, nothing more clear in paleontology than her set purposes.

The vast subkingdom of the Mollusca started well with bodily independence, fully equipped with locomotive powers, an excellent innervation, but they sold their birthright for ease and content. They soon became dependent on the movements of the waters and waited for the waves to bring them food. Compact in their protection and adaptation, these types of life have come crowding down through the ages in inexpressible variety. They and their allied phyla in the great subkingdom to which they belong have, it would seem, struggled now and again to regain their primitive independence and maintain it; but the early condemnation of the law has overawed them, and out of them all has come and can come nothing better. They had their chance. That chance was missed; for untold millions of years they have failed to improve. They still cumber the earth to teach the lesson of an incurable heritage. You who are students of ancient life know how great is the multitude of lessons like this.

None of the observations of the competent have afforded any evidence that the lines of development through such groups of lowly animals have led to anything of promise or of excellence. The ages have rolled away and left them still with us, progressed, arrested or degenerate within their own narrow limitations, as the case may be. There is no evidence to indicate that these great groups from which nothing can be expected were deprived of their equality of opportunity as contrasted with the other great subkingdoms of the annelids and the articulates, from one or the other of which, or from one and the other in succession, our own line has been derived.

The lesson, then, is this: That dependent conditions of life, however we may see them, throughout untamed nature or in our own communities, are not primitive, are not in the essence of things, but they are set back so far in the history of life that they are now, or seem to be, unavoidable and unconquerable.

These evidences I have discussed before this Society on previous occasions. The field of observation, and of inference as well, is greatly to be enlarged and well justifies the appeals that have been made on its behalf, but so much at least is indicated: that here and in analogous cases parasitic existence, in whatever group in nature, and with whatever expression in the natural assemblage or the community group, involves the essential abandonment of normal direct, upright living and the benefactors thereby are types of life which nature has cast out and aside as hopeless.

It is probably yet to be determined, at least there is no record I can find, that even in the passing of the ages nature has ever set up again on its feet an organism or group of organisms once fallen into this dejected mode of life.

It is well the State should recognize this harsh truth, which is a law. With a police power guided by intelligence and sympathy, some of the harshness in this inevitable human condition may be amelioratаed, but the paleontologist looking at the record of life on the earth says to this State: Be intelligently guided in the treatment of hereditary community parasites, defectives, congenital or confirmed misdemeanants, whatever the form of degeneration may be, by recognition of the presumption that in so far as they can not be physiologically corrected, they are abandoned types in which there lies little hope of repair. I can state this conclusion only thus succinctly without here attempting to present or argue its many ramifications.

b Soon after the great outburst of articulate life in the Cambrian, wherein, so far as our present knowledge permits, we find the lines along which have come the complicated expressions of today; somewhere in there, we may not say securely now, branched out the great phylum which led into the world of insects. We are wont to say that the first whirr of insect wings was made by the dragon flies and great cockroaches of the Devonian forests—an admission which of course implies that long earlier ages saw the differentiation of this type of life. At all events the six-legged type of articulates adapted to life in the water and air, full of vivacity and agility, with full independence, equipped with all potentialities that come from abundant innervation—this type, this six-legged articulate expression of existence, the insecta, started reasonably early on its career. It is my desire to note only in passing that, however close and direct may be the derivation of the vertebrate type from the primitive articulate stock, we have no inheritance from, and hence only a collateral interest in, this six-legged type of articulate life. Yet the outcome of development along this line has led to most extraordinary displays of morphological and psychic differentiation. A distinguished naturalist has said that the brain of an ant is the most marvelous speck of matter in existence. I hardly need, before this audience, to recall the exquisite and minute specialization in morphology, physiological function, performance, and, I should say, conscious or at least psychic behavior among the most advanced attainments of development in the six-legged articulates, the social insects. The ant colony is the ideal of differentiation of function. Its members are by birth and inheritance, food and training, destined to certain specific duties in the colony. Armies are marshaled, wars are waged, the wounded nursed; the captives are trained for their duties; gardens are planted and crops are harvested; the stock is fed and food is stored, and a score of marvelous concerted doings which amaze us by the perfection of their totality, which is—the welfare of the community. Here the individual is actually constructed nervously and physically, anatomically and physiologically, for the niche in the community which he is destined to fill. No human community where cooperative efficiency has submerged the individual and has been the objective and the attainment, no such human community has ever yet reached such an ideal of joint effectiveness as has a colony of ants. The ants are nature's great triumph, her highest performance in communistic effort and in cooperative achievement. And what has come or can come of development along this line?

Let us look back a little into the antecedents of the ants. Says Professor Wheeler, "So many genera and species of these insects appear full fledged in the early Tertiary we are compelled to believe that they must have existed in the Trias or even in the Lias, but belonged to so few genera and species, or lived in such small communities that they left no remains." This distinguished student cites 276 Tertiary species as indicative of their sudden outburst, or perhaps it would be safer to say the development of better modes for their preservation, and he has further stated that there is no reliable observation to prove that polymorphism was existent among the earliest ants of this long period. This differentiation does, however, show itself in the fossil ants of the Quaternary.

This paramount development of intellectual activity in the line of insect development, in the line of the six-legged type, would seem thus to have been accomplished largely through the same period of time when the human line was perfecting its mentality. The psychology of the two ultimate results is separated by processes and directions of development as wide apart as the poles. Neither is to be expressed, perhaps, in terms of the other. The results, too, are wide asunder—one a deadly communism, a moribund partition of labor, a lethal socialism; the other an active, progressive, and fertile individualism. For the former the student of nature's history sees no outcome. These, too, are nature's experiments. The six-legged type, with all its purposes in its highest expression, lies prostrate on the ground at our feet; it and its achievements have risen to nothing higher than an ant hill; its communistic relations and subservience are entirely apart from the true genius of humanity. Socialism and communism have been tried out and found wanting, and nature holds conspicuously before the eye of the State the warning that they have nothing either for the growth of the spirit or the progress of the intellect.

c I regard as peculiarly a doctrine of paleontology, one whose demonstration or confutation would be hopeless in the hands of the biologist, that of palingenesis, or recapitulation, or, in other words, the broad and familiar statement of the fact that each individual carries in himself and his development history, the history of the race to which he belongs, however accelerated or however retarded it may be. I am trenching familiar ground, but it is because I would remind this audience that not the mere existence but the panorama of life is essential to this conception, and that the law remains merely an assumption of probability as long as its manifestations are pursued only among creatures of high specialization. In our bodies politic the more complicated our existence becomes, the more like a tangled web of ordinances become our statutes. Forty-five thousand new statutes it is said have been enacted in the last five years in these States for some of us to trip and fall over, and just as it is difficult to pick our way through this tangle of expediential legislation, so it is likewise difficult to read in highly specialized organisms the leading of this great governing principle of biogenesis. If we do trip and fall among the entanglements of the statutes, the difficult mechanism of our present community life, let us remember that also back even of the bewildering, confusing, interlocking webs of the physiological mechanism of evolution lies, outspoken and luminant, the simpler expressions of the basic law on which rests the whole superstructure of evolution, whether of the individual or of the State.

d It is well for us, well for the State, that we read aright the teaching of the greater past upon the doctrine of majority control, for whatever enduring virtue it has takes its roots in these past procedures of life when laying the foundations of its phyla. Over and over again the dominant race has started on its career as an insignificant minority struggling for its existence against an overburden of mechanical and vital obstacles, armed only with specific virtues which have little by little fought their way into the foreground, and by so doing consummated their upward purpose. If I refer to the geological history of the phylum to which we belong, the Mammalia, it may stand for the oft-repeated procedure which has in various forms come under the notice of every paleontologist. The Prototheria, or the first of all mammals, appeared on the scene in the Jurassic, diminutive, mouselike creatures even yet retaining from reptilian ancestors the function of ovulation, possibly having already developed a marsupial pouch for their nurslings, insectivorous in dentition, creeping inconspicuously through sheltered places of the forests or among the crevices of the earth, their minute but agile brains by which they were steering their course, tremendously exceeding in proportion the brains of the giant reptiles whose variant forms constituted the majority and made them masters of earth and air and sea—whose gigantic physique and fleshly lusts had outstripped the early promise of their cephalic ganglia and left them hopelessly decephalized. Insignificant in size and number, but equipped with the vigor of phyletic youth, agile adaptability, locomotive independence left unimpaired through excessive food supply, with such equipment, good balance between cephalic and motor nerve centers, these inconspicuous and feeble folk started on their career of triumph over an overwhelming majority. Time passed and the deed was done. The agile-witted founders of the race had spread abroad through the earth. They grew vast in number and variety, adapted to all media of earth and air and sea. To them at last came the temptations of the flesh pots; they grew great in bulk, slow in body, weaker in locomotion, and feebler in proportion. They, too, had met their impasse and there was nothing beyond. The majority had arrived, but the majority had fed itself fat on the spoils of the conquest and was moribund. Once more out of this majority arose the protest of the minority and again the keener witted, better cephalized, unimpaired, but obscure and diminutive minority, strong always at the head, emerged from the welter of self-indulgence to save the race. Robbed of luxuriant food supply by a mantle of ice, its vitality quickened and stimulated by the invigorating cold, imperiously compelled by a world chill which hung on the earth unknown years to purge itself of indirection and seek the straightest way to physical salvation through the practice of simple virtues; from out of such conditions came the human stock.

If we do not recognize fully the fact that a majority control in our governments is purely a matter of expediency in the handling of civic affairs, let us remind ourselves of it on this occasion. We need only the reminder, for however often the man in the ward and the voter at the polls conceive that a majority is the paramount issue at stake, it is too often forgotten that the majority is purely numerical, while wisdom and truth may rest with the minority. Amidst the inevitable expediencies of government this is its salvation—that the minority, if clear and strong at the head, like an antecedent river, will cut down mountains of opposition.

"The triumphs of liberty have been due to minorities," said Lord Acton. "The rule of the tyrant is tyranny whether he have one head or many. The principle of absolute majority rule is as profoundly immoral and as profoundly undemocratic as is the principle of the divine right of kings. Majority rule is a practical device for the working of free institutions and not a principle without limits or bounds upon which free institutions may be based."

This is the teaching of our science; the ephemeral worth of majority control is always obvious; the voice of the people is not the voice of God.

e We have come to a point in our researches where observation and inference teach us that life originated in unicellular microbic forms under conditions which have been indirectly indicated by the Chamberlins, father and son, as governed by and intimately associated with a conjunction of soil and moisture, with obstructed air, and probably without direct exposure to the actinic action of the sunlight. There has already been interesting and substantial confirmation of the presence of actual bacteria in the most ancient rocks of continental origin antedating the Cambrian, and many well demonstrated expressions. The discovery of fossil bacteria is to be accredited to several students, Van Ingen among others, but their existence in this age preceding the primordial outburst of life, in times when by every line of sequential reasoning they should exist, this important determination is among the brilliant results of Walcott's researches.

So now every legitimate evidence of fact and deduction points to the origin of microbic unicellular life in the moist, subaerated soil away from the direct sun; and the soils of today are alive—a mighty host—with such microbic creations existing under paranerobic conditions. This army, we are coming to understand, is endowed with specialized functions; and if this statement is, and is to remain, approximately correct, then the acquisition of such special functions speaks of a long past with its gradual accumulative inheritance. It still remains to be demonstrated that the cycle of life is renewing itself from day to day by the continued transmutation of the inorganic to the organic, however such a possibility may lie in the lap of logic. But it is well for us to realize that this microbic life which in the passage of time has become adapted to such special functions that we recognize among them germs of disease as well as of benignancy, has the historic impress of hostility to the direct rays of the sun. Microbic disease is disease only from the human standpoint, from the point of view of the host of the disease-causing parasite. For the germ—the microbic parasite itself—it is normal living. I think we may well urge on the attention of pathogenists the importance of estimating the historic impress which is, in all disease-making bacteria, the natural primitive and inherited hostility to the sunlight. In the adjustments and readjustments of these parasites to special hosts and specific toxic processes some may have overcome in a measure this natural antagonism, but for the most their work is in the dark. The marvelous results which have been attained in the treatment of tetanus during the present war, by simple and constant exposure to the sunlight, encourages us to believe that in similar pathology a like treatment would be historically and logically correct.

Fifty years ago, when President Andrew D. White published his "Warfare of science and religion," he said, "A truth written upon the human heart today in its full play of emotions or passions can not be at any real variance with the truth written upon a fossil whose poor life ebbed forth millions of years ago." These fifty years since have enabled us to say with equal security that the record written on the fossil is the candle by which we must read the fate of the community, the passions and emotions of the human heart.

We have been shocked into a consciousness that not all the virtues abide in us. You may recall the ancient days of Rome when the people annually gathered to pay an offering of oil and wine, of milk and violets to the spirits of their ancestors, from the study of whose examples they gained for themselves and inculcated in others a respect for the virtuous past. So we say our *aves* to the great past out of which we and all our guiding principles in individual life, in the community, in the State, have come.

Our broader vision, which must be the bloom of our intense specialization, is like the dream of the patriarch who, resting his head on a pillow of stone, saw a ladder reaching from this earth to heaven and beheld the angels of God ascending and descending on it.

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VOL. 28, PP. 249-278, PLS. 6-9 MARCH 31, 1917

PERSISTENCE OF VENTS AT STROMBOLI AND ITS BEARING ON VOLCANIC MECHANISM *

BY HENRY S. WASHINGTON

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INTRODUCTION

A visit to Stromboli[1] in August, 1914, brought to my attention a feature of this volcano which has been overlooked generally by writers on volcanism. This is the apparent persistence in location of several of the active vents in the crater floor or "terrace" for a period of at least about a century and a half. Further consideration of this and other features of the Stromboli vents, as well as of similar features at other volcanoes, have led me to some generalizations in regard to the mechanism of volcanic action.

Briefly put, there are at Stromboli certainly three, and probably six, vents which have persisted in location for a very considerable length of time. These vents are all of small diameter, contiguous to each other within a small area, and one or more of them have been more or less continuously active. As will be shown, they are presumably the mouths of narrow, essentially vertical, disconnected conduits, which have been bored through solid strata close to the edge of a high and steep scarp. The same peculiarity of situation is found in certain parasitic vents at Kilauea and on the edge of the Val del Bove scarp at Etna. Some vents at Kilauea and at Etna and Vesuvius likewise show the features of per-

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* Manuscript received by the Secretary of the Society November 15, 1916.

[1] This name is accented on the first syllable, not on the second, as is commonly done.

sistence in location, small size and verticality of conduit, contiguity with independence of action, and others to be mentioned later. The only hypothesis that seems to be competent to explain these characters, which preclude any deep-seated or extensive explosive activity in the formation of the conduits, is Daly's "gas-fluxing" hypothesis.

As this persistence in location is one of the least well known or recognized characters of volcanoes, we shall first take up the consideration of this feature of the Stromboli vents, discussing later the application of this and other features of the volcanic vents to the explanation of the mechanism of volcanic action.

Bergeat[2] pointed out this persistence as regards one of the vents and thinks it probable for another, but does not discuss the cause or bearing of the phenomenon.

Perret also, in a recently published paper,[3] calls attention to the persistence in location of several of the vents in spite of profound changes in the configuration of the crater terrace floor, due to violent eruptions, such as those of 1907 and 1912. He, however, thinks that the feeding conduits are divergent from a central one at a comparatively small depth.

Search through the somewhat extensive literature dealing with this volcano (with the aid of Bergeat's very complete bibliography as far as 1899) has revealed much seemingly conclusive evidence of this persistence; and the establishment of the fact is so important, because of the bearing of the phenomenon on certain volcanological problems, that it seems worth while to present quite fully the documentary data.

The evidence is partly that of verbal descriptions and partly that of plans, sketches, and views of the crater terrace. The first line of evidence has been summarized by Bergeat and will be only incidentally touched on here. The second line of evidence, only alluded to by Bergeat, is in many respects much more striking and conclusive. As many of the sketches and plans are published in works which are not readily accessible, and as the inspection of a consecutive series of views and plans at different dates adds to the cogency of the argument, a quite complete set of reproductions (except of recent photographs) will be given here.[4]

The crater terrace of Stromboli is so well known and accounts of it are so numerous that a detailed description is hardly called for here. It offers exceptionally favorable conditions for observations bearing on the possible persistence of volcanic vents. In the first place, it has been the

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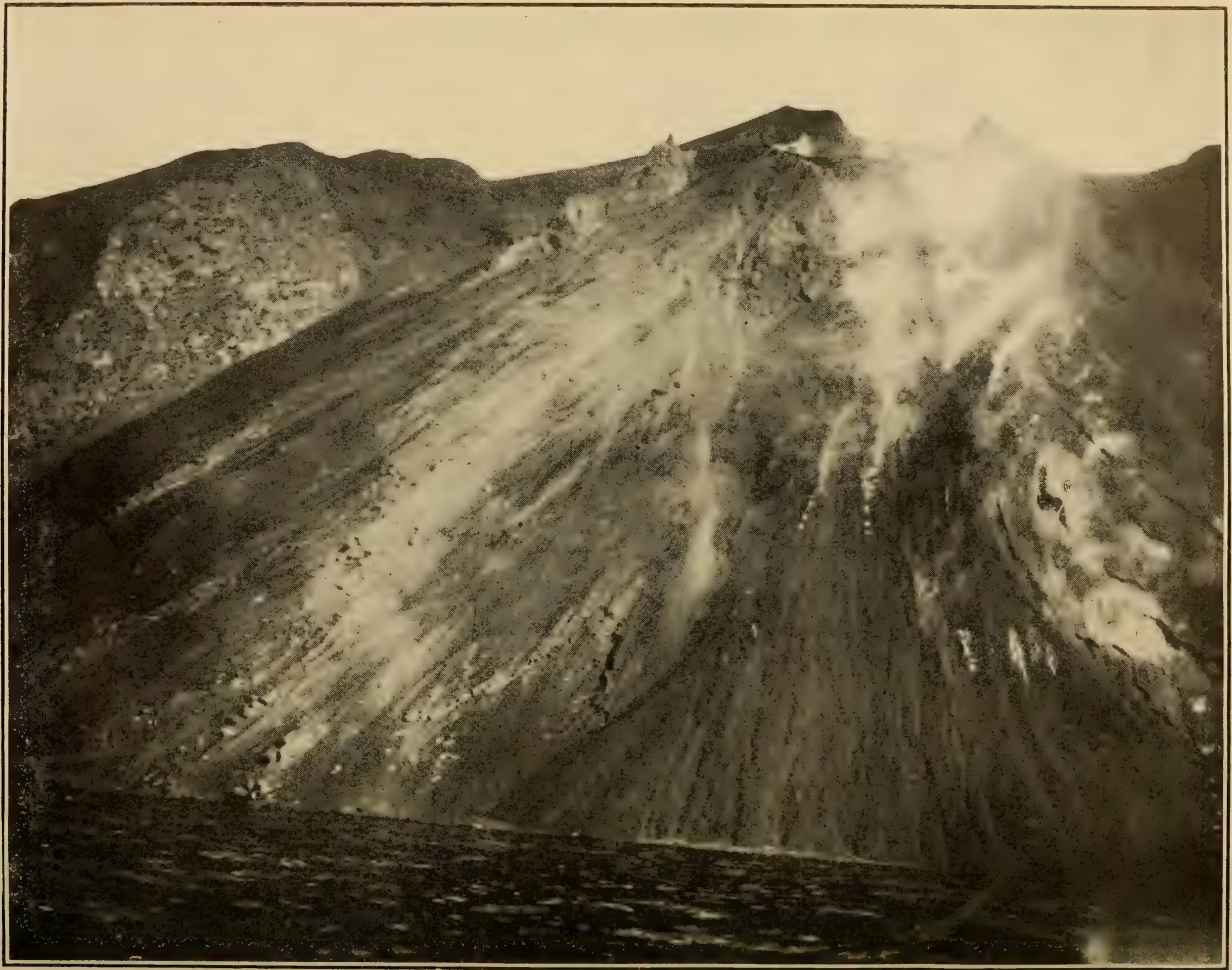
[2] A. Bergeat: Die äolischen Inseln. München, 1899, p. 34.

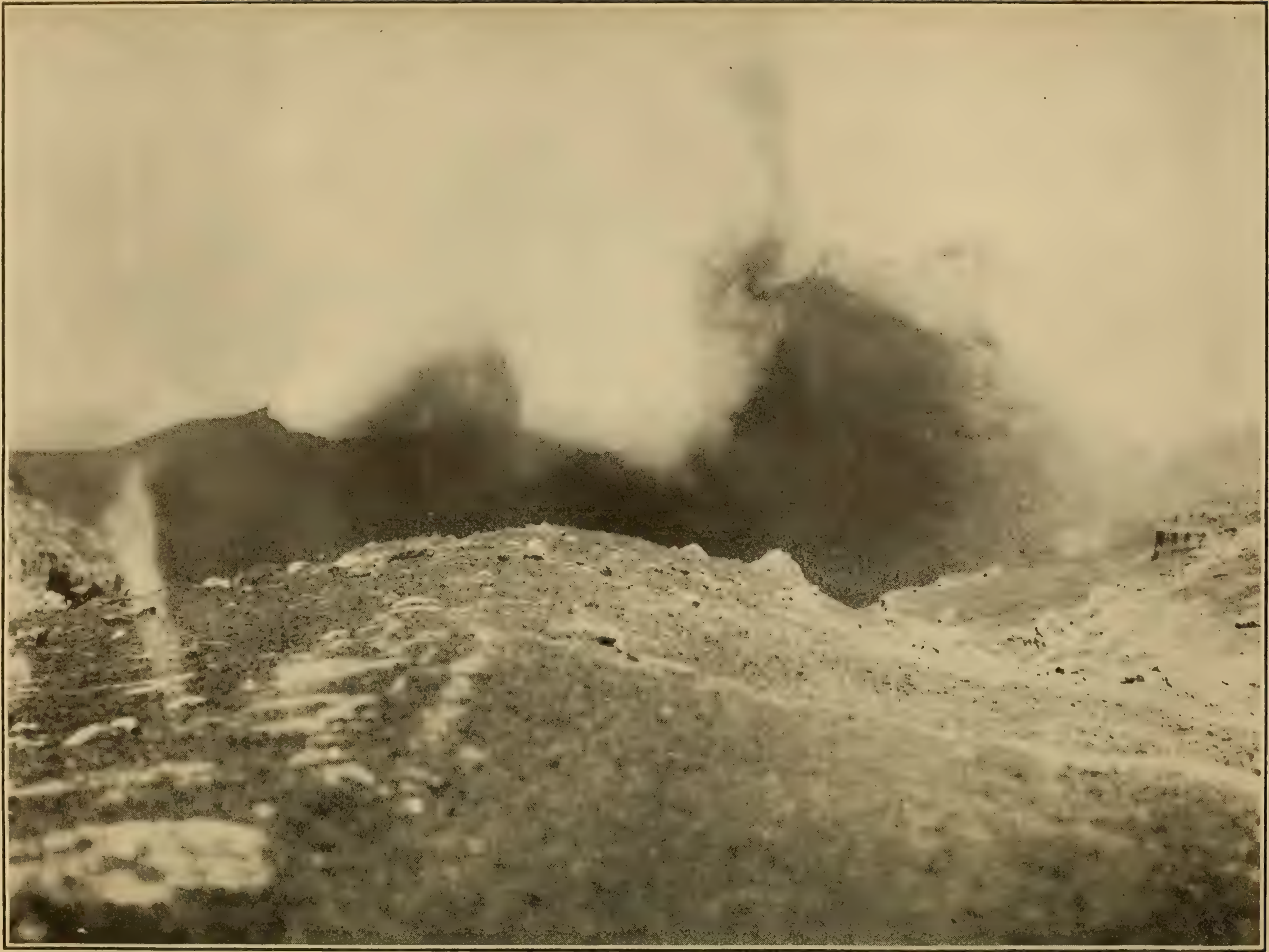
[3] F. A. Perret: Am. Jour. Sci., vol. xlii. 1916, p. 447.

[4] My thanks are due Dr. L. H. Adams for his kindness in making some of the necessary photographs.



THE SCIARRA FROM THE SEA

Photograph by Arthur L. Day, August, 1914



CRATER TERRACE OF STROMBOLI FROM THE SOUTH

Photograph by H. S. Washington, August 12, 1914 object of more or less detailed description and illustration, by a long line of foremost geologists, for more than a century and a half. Furthermore, it is unusual among volcanoes in presenting some permanent topographic features which are invaluable as points of reference for locating the several foci of activity at different times. These are the Filo del Zolfo, which bounds it on the northeast, and the Torreone or Filone di Baraonda, its southwestern boundary. Volcanic activity, at least within historic times, seems to have been confined to the area between these ridges, and the two are so prominent and distinctly outlined that one or the other (or both) will naturally be mentioned in descriptions or appear in most maps or illustrations. Finally, even in times of great activity, observation of the crater terrace is possible.

In this respect Stromboli differs from such volcanoes as Vesuvius and Etna, whose craters are approximately circular and vary constantly in size, depth, outline, and rim profile, so as to present no permanent and identifiable points of reference for any great length of time by which the positions of vents in the crater floor may be compared at different dates. In spite of these difficulties there is some evidence that also at these volcanoes a tendency to a certain persistence in location of vents may be made out. At Kilauea the same tendency may be discerned with even greater probability. These volcanoes will be discussed later.

STROMBOLI

As the location of the different vents is what concerns us here, the varying types of activity at them will not be described in this paper; also attention will be directed especially to the evidence presented by the sketches and maps, supplemented to some extent by that of verbal descriptions.

The crater was visited by me on August 7 and 12, 1914, on the latter date in company with Dr. S. Kozu, of Tohoku University. A brief description was published last year.[5] A view of the Sciarra with the crater terrace above, taken from the sea on August 14 by Doctor Day, is shown in plate 6, while plate 7 shows the terrace as seen on August 12 from a point above looking north.[6] The perspective of this view is misleading, because of the downward tilting of the camera. What appears to be a high, dark ridge is really a plain and low, elongated dome, part of the crater floor or terrace, some 200 meters below the observer. A sketch plan[7] of the terrace is given in figure 1.

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[5] Washington and Day: Bull. Geol. Soc. Am., vol. 26, 1915, p. 387.

[6] This is not the same view as that shown in plate 24 of the paper just cited.

[7] This is reproduced from figure 1 of the paper cited.

The most violent vent (though intermittently active), and apparently the largest, was that marked A (figure 1), which is just below the edge of the Sciarra and close to the Filo del Zolfo. This was explosively active when the scene was photographed, and its tall column of dark smoke is partly visible a little to the right of the center of plate 7, behind the clouds from C and D. This vent is known locally as "l'antico," and is that which Bergeat points out as seemingly to have persisted so far back as the available data allow us to judge. Adopting, with slight abbreviation, the name given it by Ponte,[8] this vent will be called the Zolfo vent.

The next most important vent, which was continuously active (B in figure 1), is situated in the northwest corner of the terrace, just above the upper edge of the Sciarra and close to, inside of, and near the lower end of the Torreone. It is the source of the upper part of the abundant white smoke to the right in plate 6, and is shown in plate 7, on the left, though the perspective makes it appear to be farther from the Torreone than it really is. This vent, as will be shown, is the second persistent vent of Stromboli, and, following Ponte, will be called the Torreone vent.

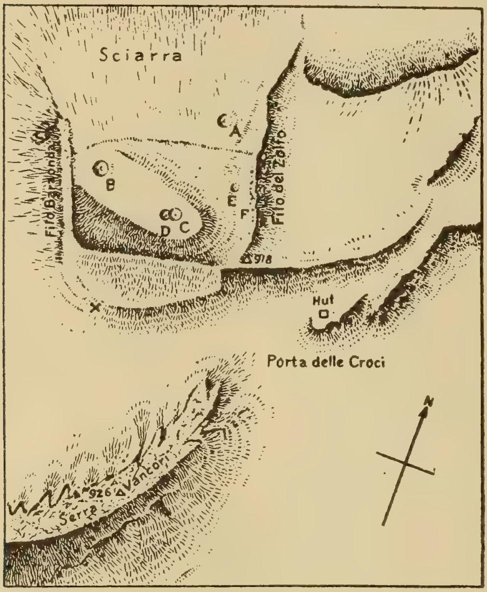

FIGURE 1.—*Plan of the Crater Terrace of Stromboli, August, 1914 (Washington)*

Near the center of the terrace were two smaller and quiet vents, C and D of figure 1, which also appear in the center of plate 7. These may be called the Central vents. Below the line of fumaroles, inside the wall of the Filo del Zolfo, was a fifth vent (E of figure 1), which had a very small diameter, and at rather long intervals "blew off" with a loud blast and the emission of a very tall and narrow column of smoke. It appeared to be more or less choked by scoria and ashes. The depression is discernible in plate 7. It will be known as the Fumarole vent.

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[8] G. Ponte: Rend. Acc. Linc. (5), vol. xxv, 1916, p. 374.

Earlier in 1914 Stromboli was visited by O. de Fiore, who, with three companions, succeeded in descending to and going over the terrace itself.[9] The sketch map he gives on his plate LXX is reproduced in figure 2. From this and his brief preliminary description it is clear that his number 4 is my B, the Torreone vent. His subsidiary vent 4*a*, which was quiet in April, would seem to have filled up by August. It is reasonable to believe that his number 5 corresponds to my D, and his 6 and 7 to have coalesced to form my C, which, as was stated in the previous paper, was larger and later than D. His 5, 6, and 7 would thus be in the general location of the Central vents. His number 1 was probably in the neighborhood of my E, the Fumarole vent, but this part of the terrace appears to have been much filled up between April and August, probably largely by ejecta from the Zolfo vent, his number 2, which resumed activity after his visit. His number 3, between the Zolfo and Torreone vents and a little way down the Sciarra, was not active or visible in August, but was violently so in 1915. Following Ponte, this will be called the Sciarra vent.

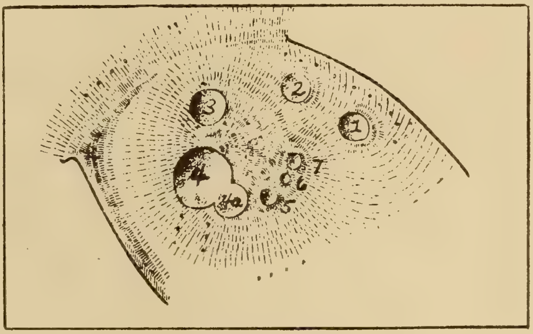

FIGURE 2.—*Plan of the Crater Terrace of Stromboli, April, 1914 (de Fiore)*

The great eruption of July-November, 1915, has been described by F. A. Perret in a paper recently published.[10] The condition after the eruption, in December, 1915, has been described by G. Ponte in a preliminary note,[11] with a photograph of a plaster model of the summit of Stromboli. The Zolfo, Torreone, and Sciarra vents were active, the last being the source of lava flows, and there was also a vent (Ponte's D) in the vicinity of my E, the Fumarole vent.

Having thus obtained an idea of the conditions in 1914, as a starting point, we may first consider the more recent maps and sketches, which are reproduced in figures 1 to 13. In comparing these it must be borne in mind that none of the plans was based on an instrumental survey, but that they were all free-hand sketches; also the oblique perspective, the generally very irregular surface of the terrace, and sometimes the abundance of smoke, have sometimes rendered the *exact* relative location of the vents somewhat difficult, if not impossible. It is here that the presence of the eastern and western bounding ridges proves to be invaluable for orientation. On the other hand, the plans and sketches were made by different observers, and independently of any theory of persistence in location of the vents for any great length of time.

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[9] O. de Fiore: Zeits. Vulk., vol. i, 1915, p. 233, and plate lxx.

[10] F. A. Perret: Am. Jour. Sci., vol. xlii, 1916, p. 443.

[11] G. Ponte: Rend. Acc. Linc. (5), vol. xxv, 1916, p. 373.

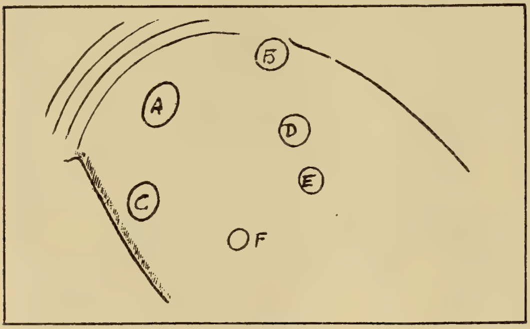

FIGURE 3.—*Plan of the Crater Terrace of Stromboli, August, 1912 (Perret)*

As the number of illustrations is somewhat large, considerations of space necessitate a very brief discussion of each and comparison with its successor, the one previously described, it being understood that the figures are presented in an inverse chronological order. This order is adopted because the more modern plans are not only more reliable, but present the situations of the vents more clearly than the earlier views, which often leave something to be desired in these respects and can only be regarded as confirmatory of the evidence furnished by the later illustrations.

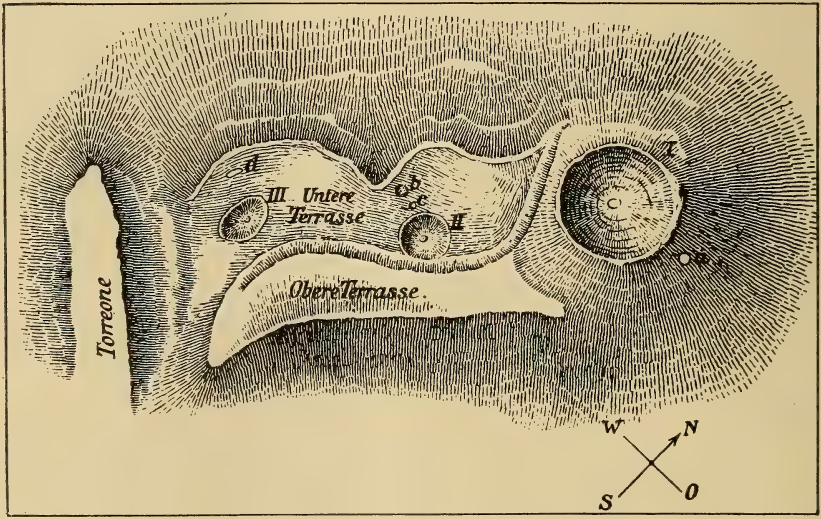

FIGURE 4.—*Plan of Crater Terrace of Stromboli, May, 1906 (Wegner)*

Figure 3 is a plan by Perret of the conditions after the eruption of 1912, as published by de Fiore.[12] It does not differ materially from that of the conditions in April, 1914.

In figure 4 is reproduced a plan of the vents in May, 1906, by Wegner,[13] which also is the basis of the map of the summit region of Stromboli given by Sieberg,[14] who could not see the terrace because of the smoke. Disregarding the surface topographic details and considering only the vents, I is clearly the Zolfo vent (it is called the "bocca antiqua" by Wegner) and III is the Torreone. Wegner's II probably is the Sciarra vent, though it is placed higher up and on a line between I and III.

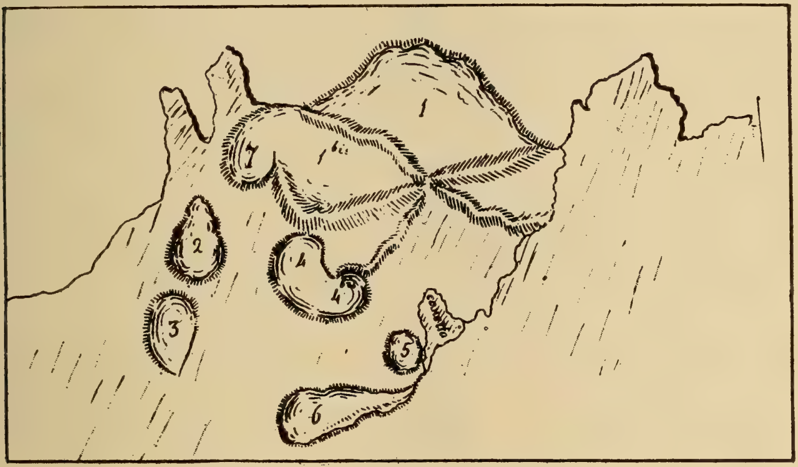

FIGURE 5.—*Plan of Crater Terrace of Stromboli, May, 1904 (Ricco)*

The small vents *a, b, c, d* are scarcely more than fumaroles, to judge from their sizes and descriptions, though *d* may be the remains of a small vent noted by Ricco in 1904.

Figure 5 is a rough half sketch and half plan of the vents in May, 1904, drawn by D. Vasello and published by Ricco.[15] Here the Torreone and the Filo del Zolfo are seen in perspective, with the vents in plan, the point of view being to the northwest of the Torreone. From the description accompanying the not very clear figure it would appear that 2 (near the base of the Filo del Zolfo) is the Zolfo vent, and that 6 (at the end of the Torreone), which was very active, is the Torreone vent; 3 is apparently the Sciarra vent; 4 and 4′ obviously occupy the place of my C and

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[12] O. de Fiore: Zeits. Vulk., vol. i, 1915, p. 229, plate lxx.

[13] T. H. Wegner: Neu. Jb., Cb. 1906, p. 562.

[14] A. Sieberg: Erdbeben-und Vulkankunde Süditaliens. Jena, 1914, p. 195.

[15] A. Ricco: Boll. Soc. Sism. Ital., vol. x, 1904, p. 38.

D and the 5, 6, 7 of de Fiore—the Central vents. Vent 7, spoken of as new, is near my E, the Fumarole vent. It is somewhat difficult to understand the starfish-like set of ridges, but 1 and 1′, close under the southern scarp, represent a pair of large vents which developed earlier and which also were prominent in the eruption of 1907. From its position near the southern bounding scarp this may be called the Scarp vent.

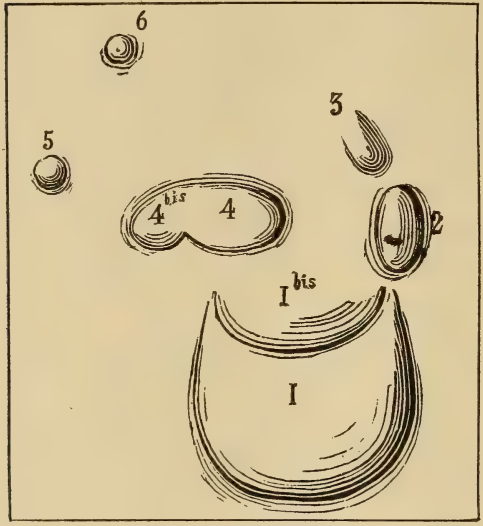

FIGURE 6.—*Plan of Crater Terrace of Stromboli, November, 1899 (Arcidiacono)*

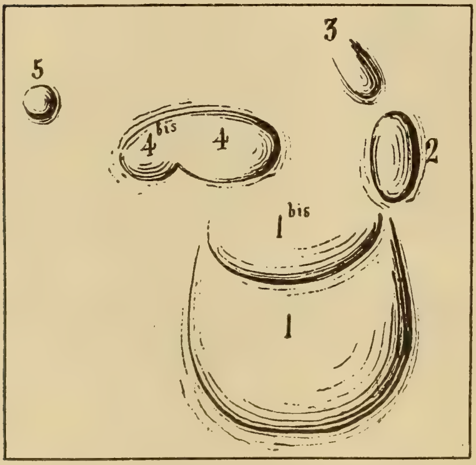

FIGURE 7.—*Plan of Crater Terrace of Stromboli, November, 1898 (Arcidiacono)*

Figures 6[16] and 7[17] are very rough plans of the vents in November, 1899, and November, 1898, the latter by A. Sembrine. The correspondencies between the different vents in these two and in figures 1 and 3 are so obvious that they need not be pointed out. Number 6 of figure 8 represents, of course, an opening of the Sciarra vent.

Figure 8, a sketch of the condition in November, 1895, by Ricco,[18] is rather unsatisfactory, and it is difficult to identify some of the vents. The view was probably taken from the south. Number 1 is obviously the large Scarp vent seen in previous figures. A vent, number 2, behind the edge of the Sciarra, not seen in the figure, but mentioned in the text, corresponds with the Zolfo vent.

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[16] S. Arcidiacono: Boll. Soc. Sism. Ital., vol. v, 1900, p. 113.
[17] S. Arcidiacono: Ibid., vol. iv, tav. ii, 1898.
[18] A. Ricco: Boll. Soc. Sism. Ital., vol. ii, 1896, p. 96.

Vent 3 is approximately in the position of the Sciarra vent. Vents 4 and 5 (the latter said to be doubtful) evidently correspond to the Torreone vent. It will be recalled that this vent was double in April, 1914 (figure 2).

Bergeat's plan and sketch of the terrace[19] in October, 1894, are shown in figures 9 and 10. His IV is, of course, the "Antico" or Zolfo vent, and I, equally as obviously, is the Torreone vent. Whether II and III correspond to the Sciarra vent or to the Central vents, or are independent, is uncertain. Bergeat could only observe the terrace from above, not from below the Torreone, and the linear arrangement of these between I and IV may be more apparent than real, and due to the somewhat difficult perspective. I am inclined to believe that they are in reality the Central vents, but the sketch implies that possibly they are only fumaroles. At his visit there was, apparently, no activity at the Scarp or the Fumarole vents, but the former is shown in the foreground of the sketch (figure 10).

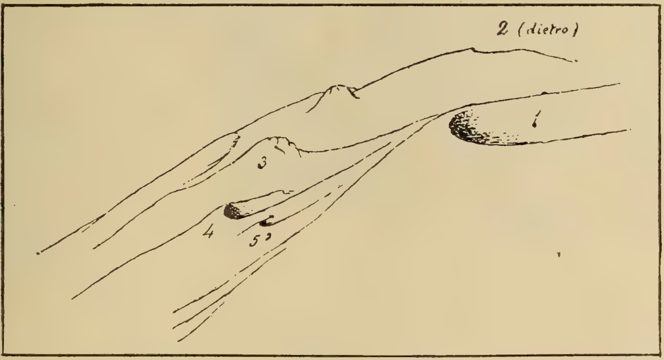

Figure 8.—*Sketch of Crater Terrace of Stromboli, November, 1895 (Ricco)*

The plan and sketches given in figure 11[20] show the conditions in July, 1891. This appears to be the earliest published plan. Here, judging from the plan, the description in the text, and some photographs (not reproduced here), number 2 would appear to be the Zolfo vent, and number 3 is probably the Sciarra vent. Number 5 is the Torreone vent and number 4 a Central vent. Great confidence, however, is not placed in these identifications, though obviously the Zolfo, Torreone, and Scarp vents are present.

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[19] A. Bergeat: Op. cit., table x, and figure 3, p. 31.

[20] A. Ricco and G. Mercalli: Ann. Uff. Cent. Met. Ital. (2), vol. xi, part iv, tav. ii, 1892.

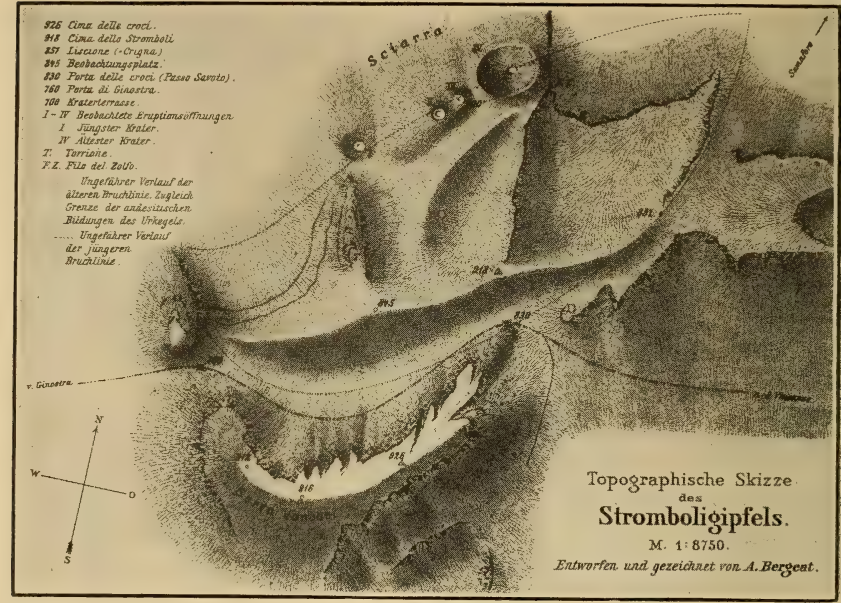
926 Cima delle croci.
918 Cima dello Stromboli
857 Liscione (-Crigna)
845 Beobachtungsplatz.
830 Porta delle croci (Passo Savoto).
760 Porta di Ginostra.
700 Kraterterrasse.
I - IV Beobachtete Eruptionsöffnungen
I Jüngster Krater.
IV Ältester Krater.
T. Torrione.
F.Z. Filo del Zolfo.
Ungefährer Verlauf der älteren Bruchlinie. Zugleich Grenze der andesitischen Bildungen des Urkegels.
..... Ungefährer Verlauf der jüngeren Bruchlinie.
Sciarra
845
830
926
918
v. Ginostra
N
W
O
S
Topographische Skizze des Stromboligipfels.
M. 1:8750.
Entworfen und gezeichnet von A. Bergeat.

FIGURE 9.—*Plan of Crater Terrace of Stromboli, October, 1894 (Bergeat)*

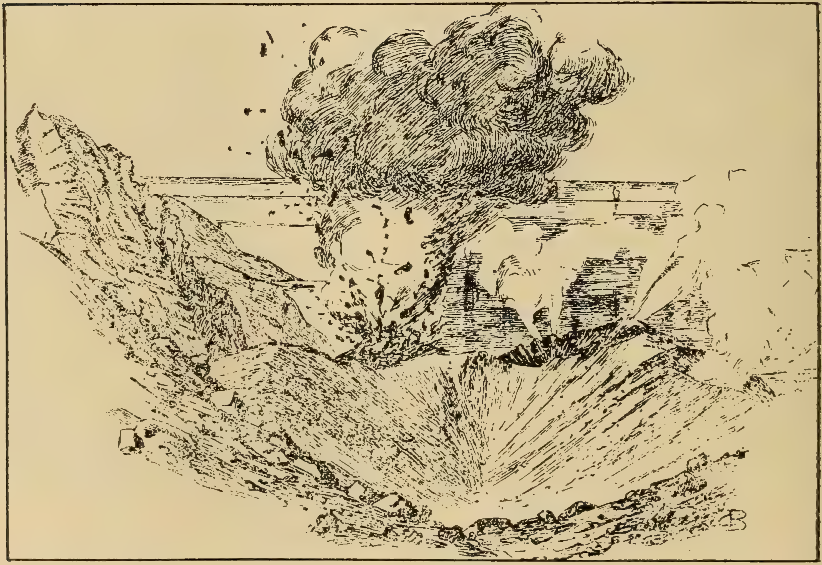

FIGURE 10.—*Sketch of Crater Terrace of Stromboli, October, 1894 (Bergeat)*

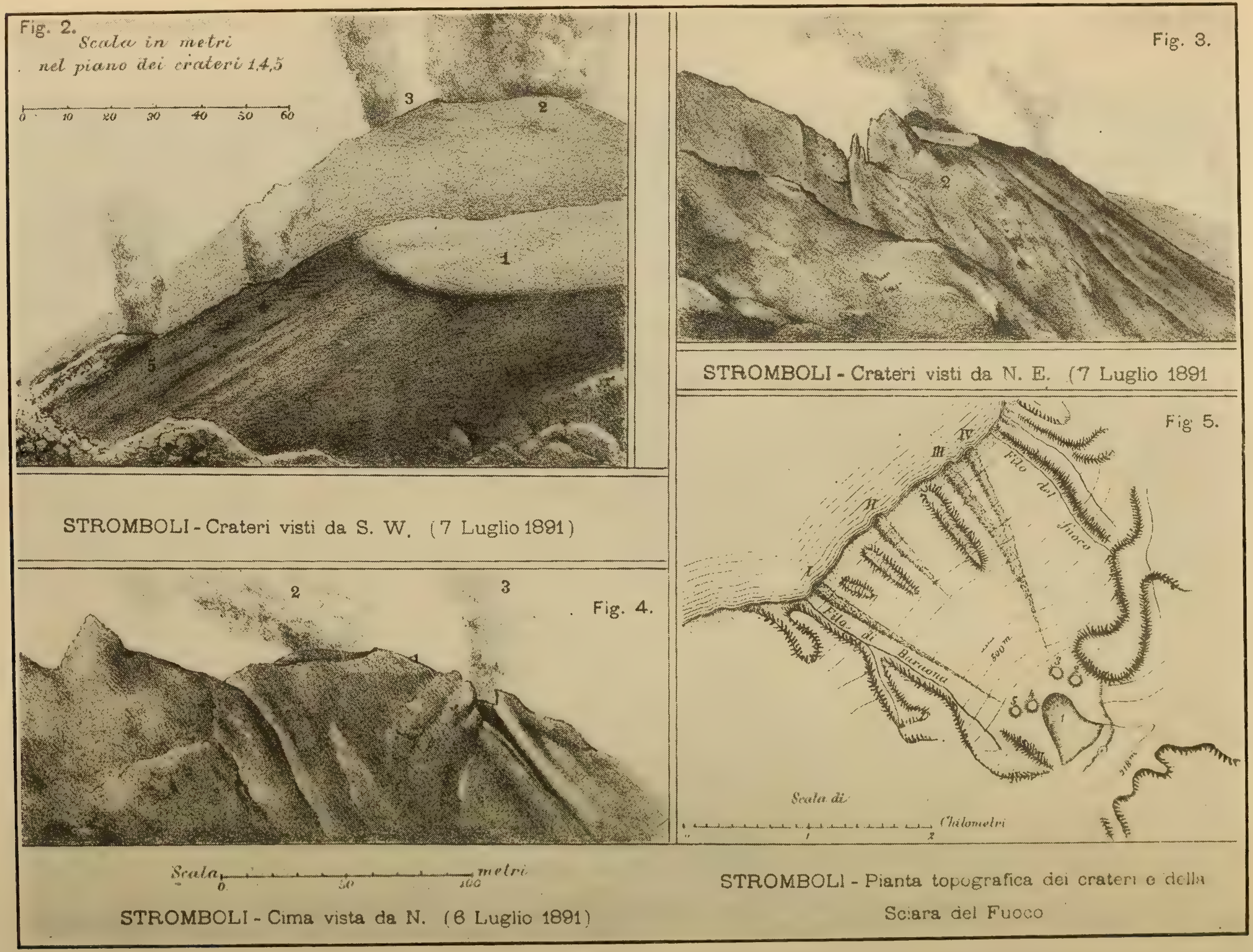
Fig. 2.
Scala in metri
nel piano dei crateri 1,4,5
0 10 20 30 40 50 60
3
2
1
5
Fig. 3.
2
Fig. 4.
2
3
1
Scala 0 50 100 metri
Fig 5.
I
II
III
IV
Filo di Baraona
Filo del fuoco
500 m.
1
Scala di Chilometri
0 1 2

STROMBOLI - Crateri visti da S. W. (7 Luglio 1891)

STROMBOLI - Crateri visti da N. E. (7 Luglio 1891

STROMBOLI - Cima vista da N. (6 Luglio 1891)

STROMBOLI - Pianta topografica dei crateri e della Sciara del Fuoco

FIGURE 11.—*Plan and Sketches of Crater Terrace of Stromboli, July, 1891 (Riccò and Mercalli)*

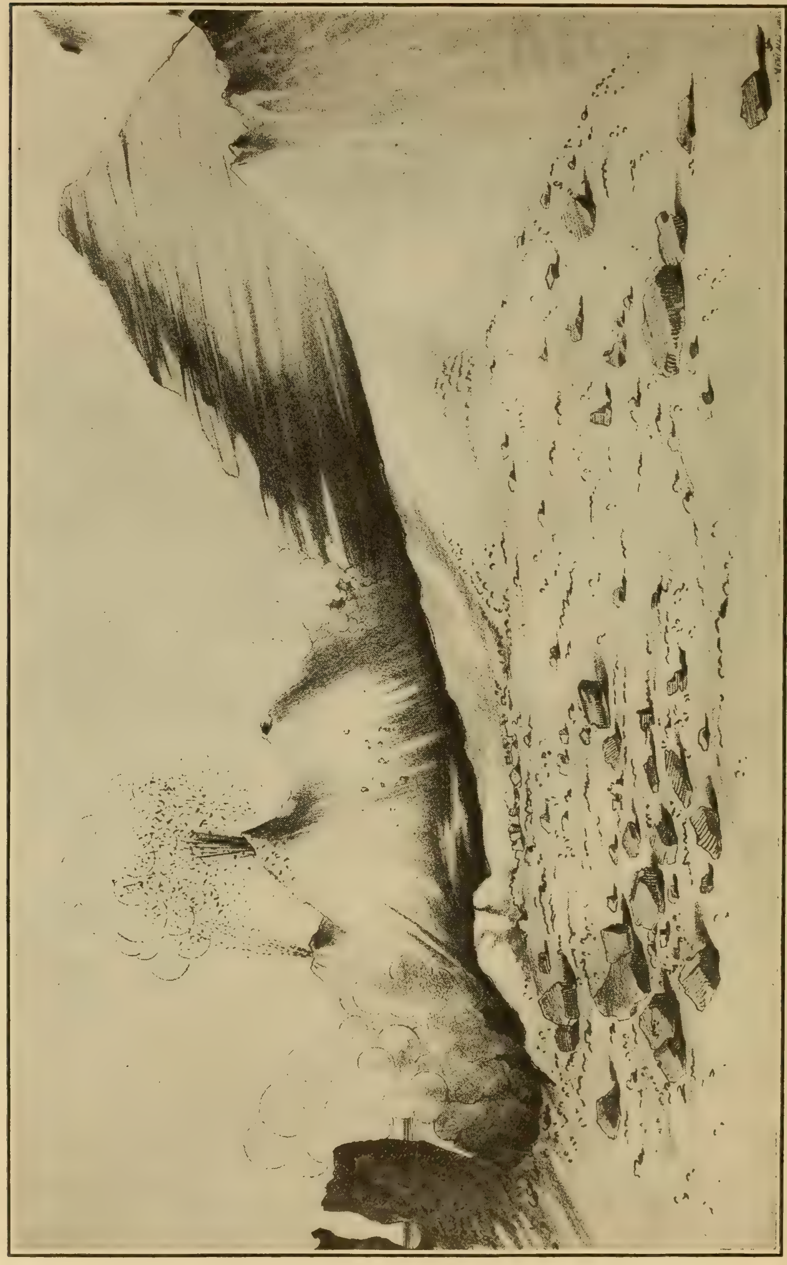

FIGURE 12.—*Sketch of Crater Terrace of Stromboli, March, 1889 (Mercalli)*

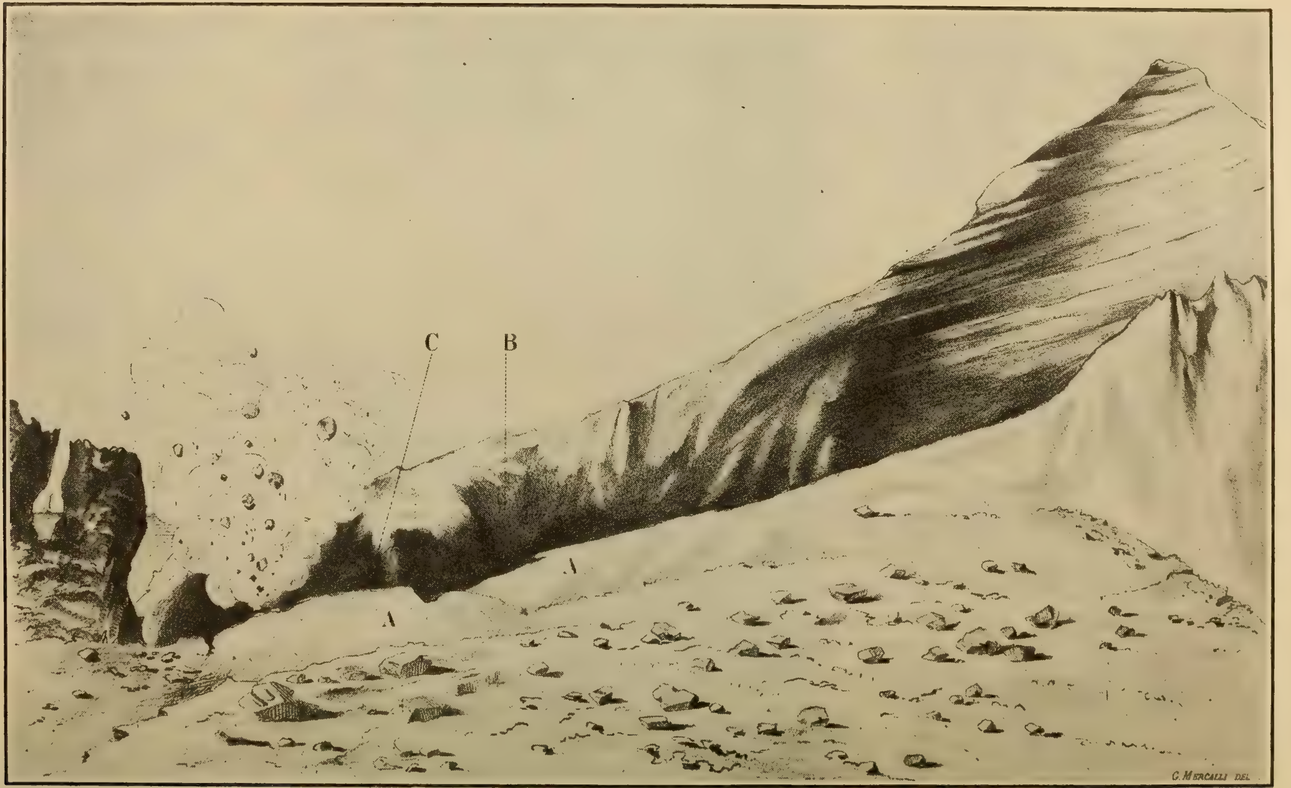
C
B
A
A
C. MERCALLI DEL.

FIGURE 13.—*Sketch of Crater Terrace of Stromboli, September, 1888 (Mercalli)*

It is noteworthy, in reading the descriptions of the vents from 1891 to 1907 by the Italian observers, Ricco, Mercalli, Arcidiacono, and Platania,[21] that, whether plans are given or not, the different vents are constantly referred to, in describing their activity, by the same numbers, and their persistence in location is either tacitly assumed or explicitly stated.

Figure 12 is a sketch by Mercalli of the terrace on March 1, 1889.[22] Both the Torreone and Zolfo vents were active, as well as one which Mercalli calls the "conetto centrale," and which would appear to have been the Sciarra vent. The situation six months earlier (September 3, 1888) is shown in figure 13,[23] when the activity was confined chiefly to the Torreone vent.

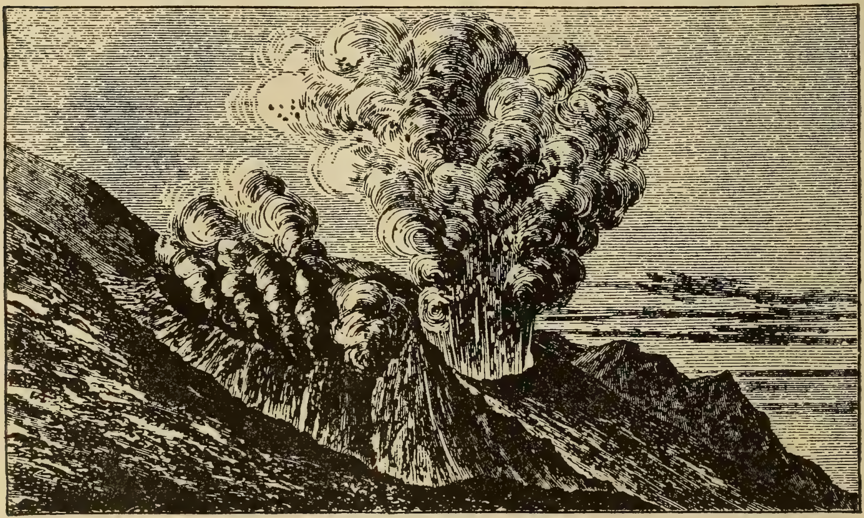

FIGURE 14.—*Sketch of Crater Terrace of Stromboli, April, 1874 (Judd)*

There appear to have been published no plans of the terrace or sketches of the several vents prior to 1888, such as we have been examining. There are, however, a few pictures and drawings which furnish some information. Some of them are more remarkable for their quaintness and Giottesque charm than for their strict fidelity to nature. Unfortunately, as will be seen, they were all taken from east or west of the upper part of the Sciarra or from below it, and so show little or nothing of the terrace floor. We thus get no clue from them as to the vents on this, but are afforded information concerning the Zolfo, Sciarra, and Torreone vents, the sites of which are visible from the points of view mentioned.

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[21] G. Platania: Ann. Uff. Cent. Met. Ital., vol. xxx, part i, 1910, p. 1.
[22] G. Mercalli: Ann. Uff. Cent. Met. Ital. (2), vol. x, 1892, p. 248, and tav. xii.
[23] G. Mercalli: Op. cit., p. 246, and tav. xi.

Figure 14 shows a sketch by Judd[24] of an eruption in April, 1874, seen from northeast of the terrace. Here the fumaroles on the east side of the Filo del Zolfo are seen to be active, and just inside the Filo, at the head of the Sciarra, is the Zolfo vent, sketched during an explosion.

A sketch by Bornemann[25] of the upper end of the Sciarra in 1856, taken from west of the lower end of the Torreone, is shown in Figure 15. The Zolfo, Sciarra, and Torreone vents were present, only the two latter to be seen in the sketch, and the volcano showed little activity.

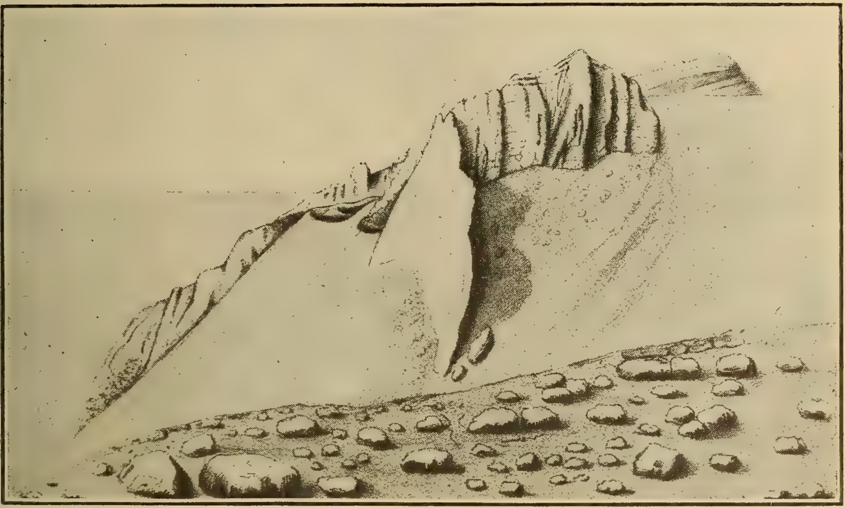

FIGURE 15.—*Sketch of Crater Terrace of Stromboli, 1856 (Bornemann)*

It may be pointed out, as confirmatory of the general correctness of the two sketches, figures 14 and 15 (taken from opposite ends of the Sciarra edge), that the point forming the end of the Filo del Zolfo (immediately to the left of the Zolfo vent) in figure 14 is to be seen in the pinnacle of figure 15; and also the general outline of the Torreone corresponds in both, though seen from opposite sides.

A very striking view of the crater terrace in September, 1830, by Bylandt Palsterkamp,[26] is shown in figure 16. This is quite at one with his naïve account of the terrifying ascent of Stromboli and the view of

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[24] J. W. Judd: Volcanoes, New York, 1890, p. 14. A similar view is also published by Judd in Geol. Mag. (2), vol. ii, 1875.

[25] J. G. Bornemann: Zs. Deut. Geol. Ges., vol. xiv, taf. x, 1862.

[26] Bylandt Palsterkamp: Theories des Volcans, Paris, 1835, pl. xiv, cf. vol. ii, p. 306.

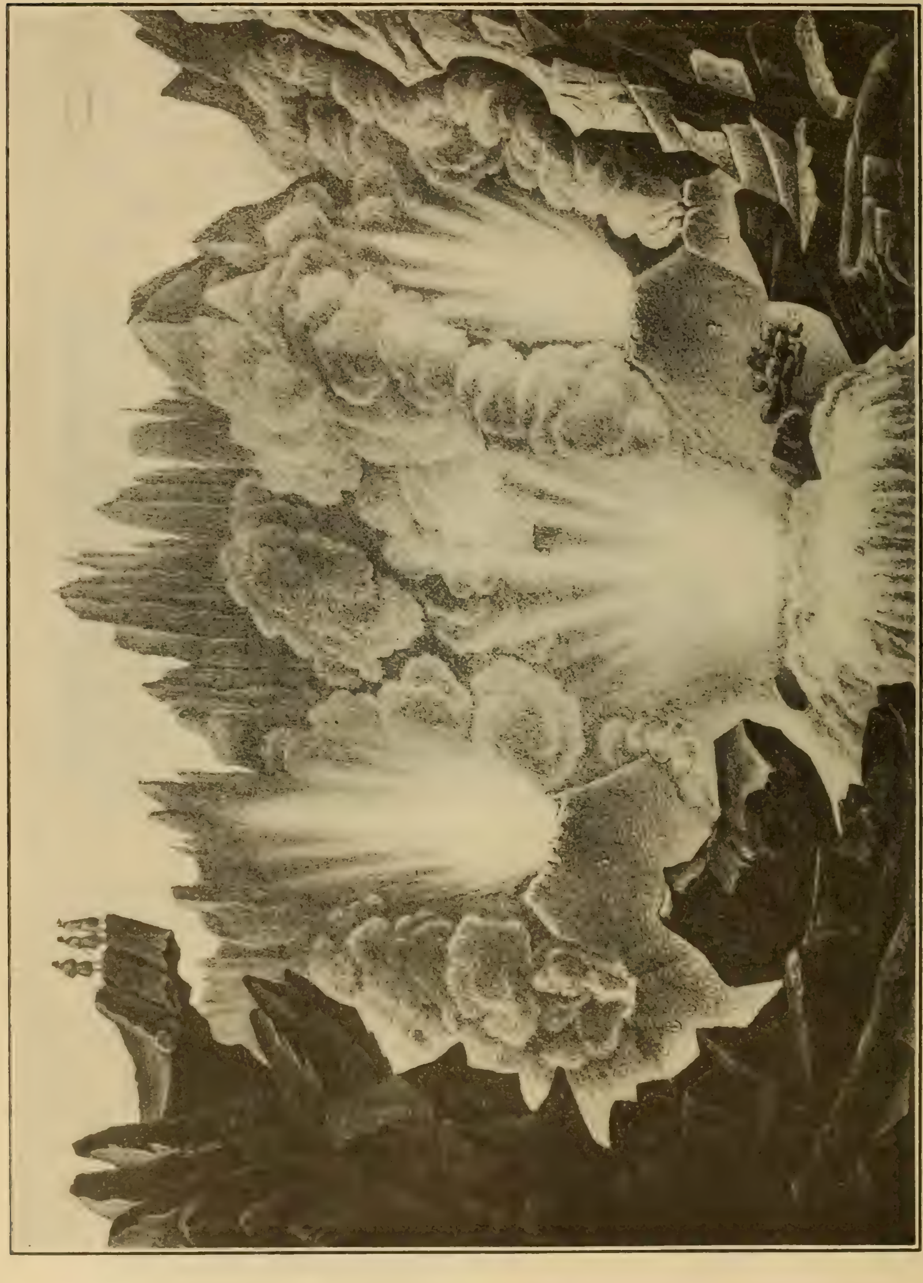
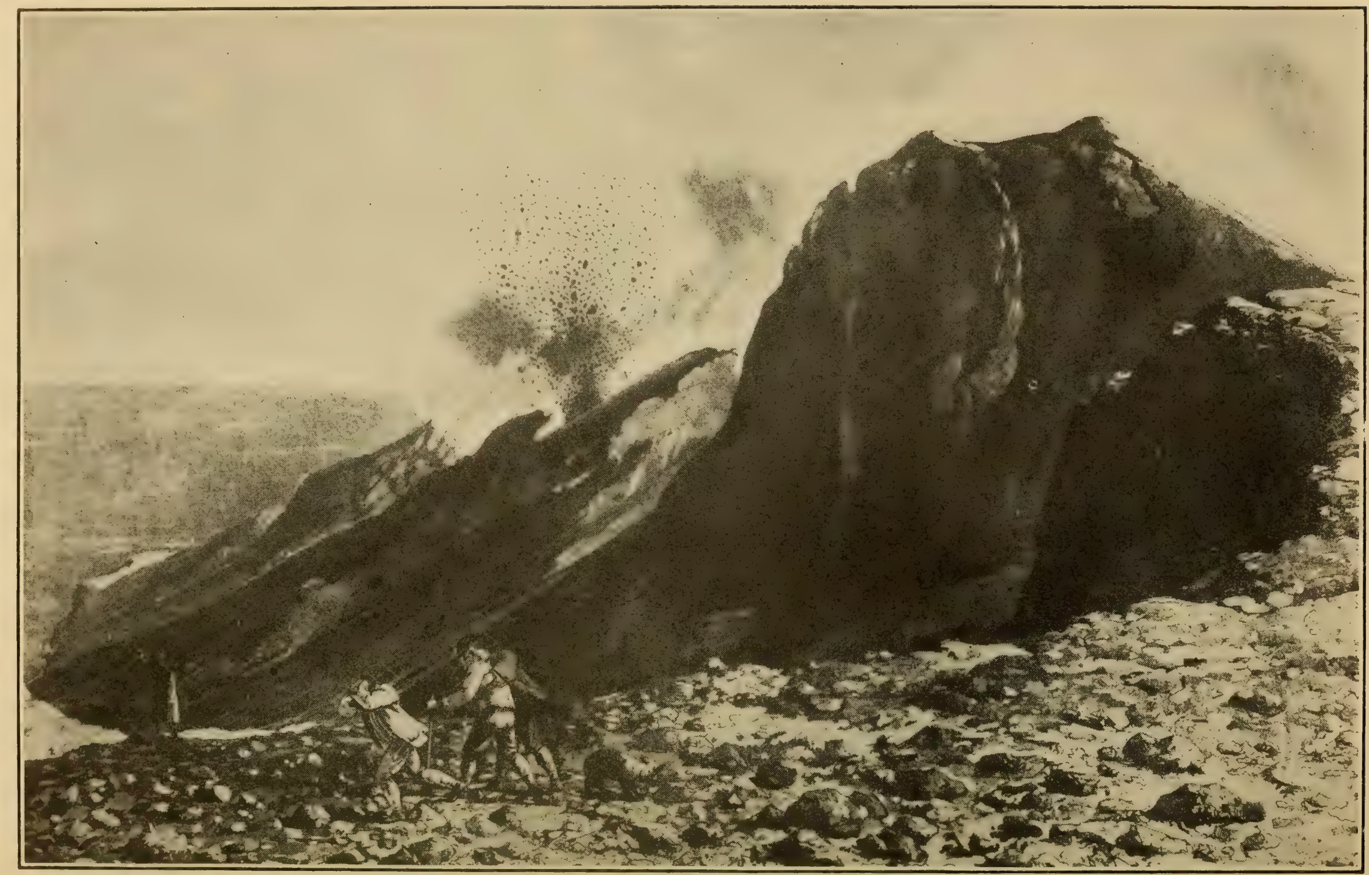


FIGURE 16.—*Sketch of Crater Terrace of Stromboli, September, 1830 (Palsterkamp)*



CRATER TERRACE OF STROMBOLI

Houel, 1776

the crater. In spite of its peculiarities,[27] which led Bergeat[28] to remark, "Seine abenteurliche Zeichnung, aus der man sich unmöglich orientieren kann," one can readily make out the foundation of fact underlying its Brocken-like character and see that the general features and the positions of the main vents correspond in a general way with those which we have noted in preceding descriptions. Unreally jagged as they are, we see the boundaries of the crater terrace, with the southern scarp and the two lateral ridges. The Zolfo and Torreone vents are here, with the Sciarra vent (number 3) between them, at the beginning of the Sciarra, while behind, amid the clouds of vapor, is a representation of what may be supposed to be the Central vents.

Although not germane to the subject, it is interesting to note the presence of a smoke ring rising from the Torreone vent (number 2 of plate)—the first representation of a phenomenon afterward photographed and described by Perret.[29] It may be remarked that Palsterkamp (volume II, page 343) attributes the rings to phosphuretted hydrogen.

Figure 17 is a reproduction of Spallanzani's quaint engraving[30] of Stromboli in October, 1788. Here, with the aid of his graphic description and a little imagination, we can recognize our old friend, the Zolfo vent, though in somewhat fanciful disguise, while on the west (east in the text) a column of smoke rises from the Torreone vent. These would seem to have been the only vents active at this time. The line of fumaroles along the Filo del Zolfo is clearly shown.

The next illustration, plate 8, is Houel's[31] artistic colored lithograph of the crater in 1776, taken from the west. In this the Sciarra vent is in full activity, the Zolfo vent also active beyond it, and the Torreone vent less so. There is much "smoke" above the crater terrace, indicating the presence of some active vents there. Houel's plate LXXI, of the Sciarra from the sea, also shows the Sciarra vent.

Comparing this with Bornemann's sketch (figure 15), both taken from about the same spot, it is interesting to note (again as confirmatory of the general correctness of both) that the outlines of the Torreone in each are essentially alike, even to details, and that the somewhat sharp shoulder below the end of the Filo del Zolfo in figure 15 is clearly seen in plate 8. These points of identity are especially noteworthy, as the one was made eighty years later than the other.

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[27] There is a discrepancy between the text and the plate as regards the numbering of the vents 1, 2 and 6, 5; probably an engraver's error. It does not affect the argument.

[28] Bergeat: Op. cit., p. 32.

[29] F. A. Perret: Amer. Jour. Sci., vol. xxxiv, 1912, p. 405.

[30] L. Spallanzani: Viaggi alle due Sicilie. Milan, 1825, vol. ii, plate iii; cf. pp. 267-270.

[31] J. Houel: Voyage Pittoresque des Iles de Sicile, etc., Paris, 1782, pl. lxxii.

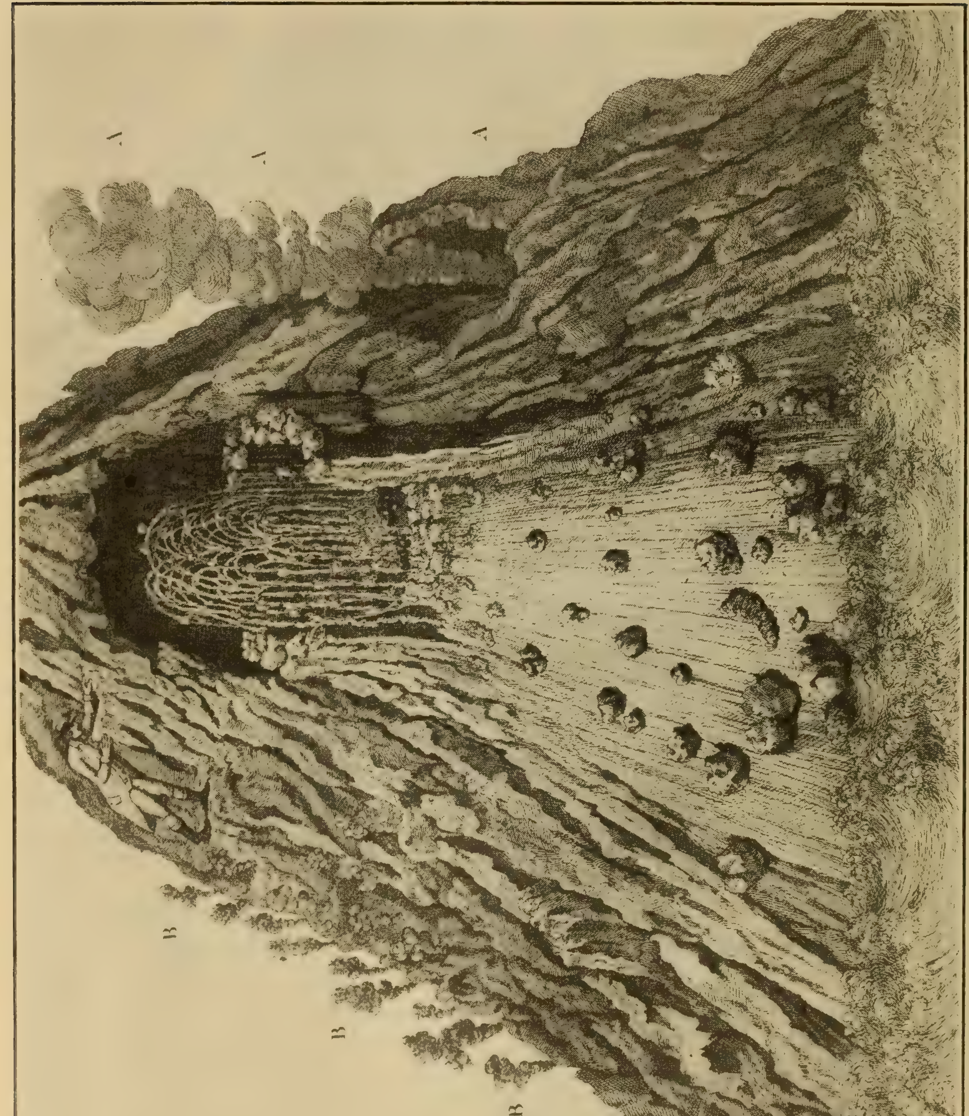
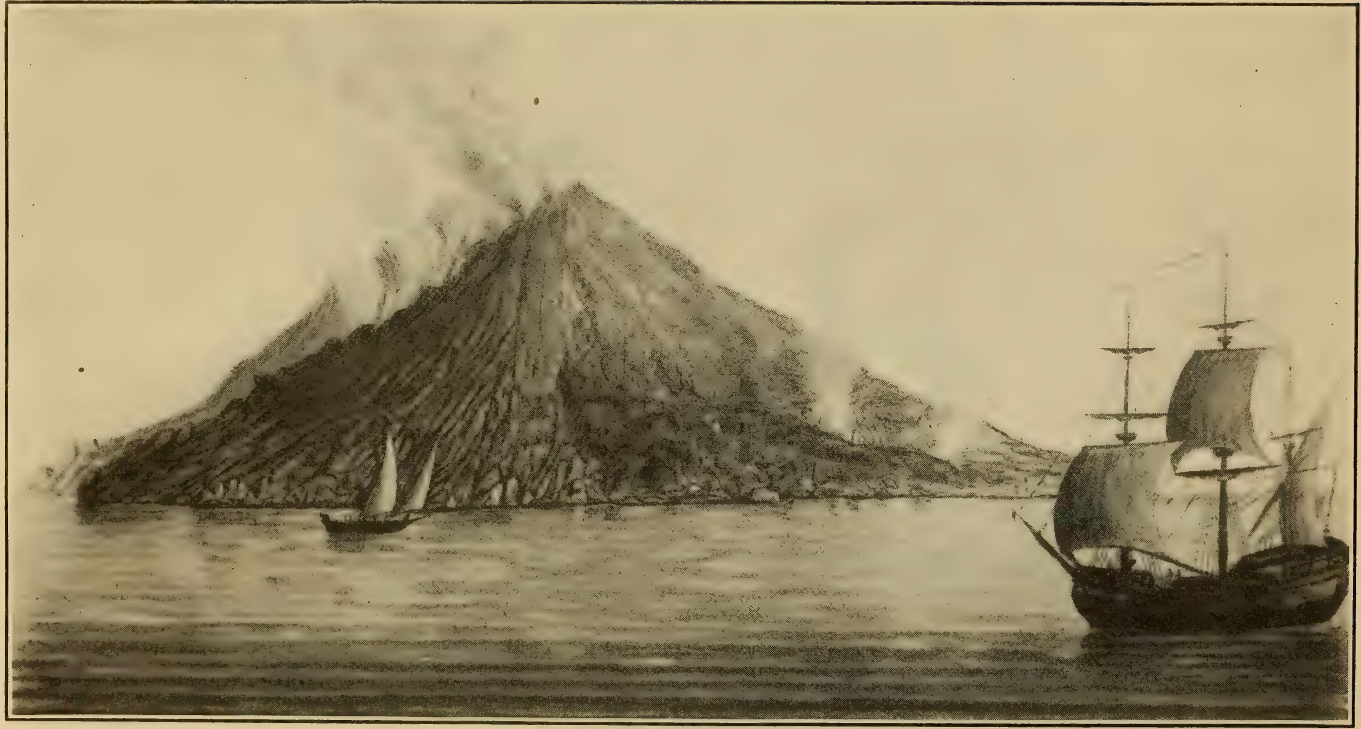


FIGURE 17.—*Sketch of Stromboli, 1788 (Spallanzani)*



STROMBOLI FROM THE WEST

Hamilton, 1776

The last and earliest illustration of Stromboli that I have found, plate 9, from Hamilton's large and classic work,[32] represents the island in 1768. Here the Zolfo, Sciarra, and Torreone vents in full activity are clearly shown, at the upper edge of the Sciarra, and a fourth farther back, about in the center of the terrace. The text accompanying the plate mentions lava streams flowing from the crater and from the "spots" marked 2, near the west end of the island.

To the above illustrational evidence might have been added the many photographs by Tempest Anderson, Lacroix, Perret, Platania, and others—taken either from above or from the northwest—which show especially the activity of the Torreone, Sciarra, and, less often, the Zolfo vents during recent years.

In order to obtain a comprehensive survey of the occurrences of the different vents shown in the preceding figures, they are summarized in Table I. In this the deplorable confusion in designating the several vents by letters and numbers is very evident. It was to avoid this that names have been given in this paper to the vents.

A fact brought out by the table, plans, and sketches, and one which is still more emphasized when supplemented by the verbal descriptions, is the great variation in the number of vents active at different dates. At times as many as seven or even eight are reported, while at others the number may sink to two or even but one, while in 1897 none of the vents was explosively active. It is this feature which has led many writers to consider the vents of Stromboli very variable and to overlook the persistence in location of some of them. When very numerous vents are reported, it is probable in some cases and certain in others (as with Wegner in 1906) that some of the so-called vents are in reality small fumaroles.

From the above survey and an inspection of the table (supplemented by many verbal descriptions) it will be fairly evident that foci of activity have existed since 1768 continuously, or almost so, at or near the site of the Zolfo and Torreone vents of 1914, and rather more intermittently at or near the site of the Sciarra vent. In view of the nature of the evidence and the absence of any accurate surveys, it can not be asserted that these foci have always occupied *exactly* the same locations. But when we consider that the positions of two of them are fixed with considerable accuracy by the presence of the near-by bounding ridges, while that of the other is more or less nearly half way between and slightly below the other two, we can be fairly confident that, in the case of these three, departure from

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[32] Sir William Hamilton: Campi Phlegraei. Naples, 1776, plate xxxvii.

TABLE I.—*Tabulation of the Active Vents at Stromboli*

Figure.	—	3	4	5	6	7	8	9	10	11	13	14	15	16	17	18	19	20	21
Author and date.	Ponte, December, 1915.	Washington, August, 1914.	De Fiore, April, 1914.	Perret, August, 1912.	Wegner, May, 1906.	Ricco, May, 1904.	Arcidiacono, November, 1899.	Arcidiacono, November, 1898.	Ricco, November, 1895.	Bergeat, October, 1894.	Ricco and Mercalli, July, 1891.	Mercalli, March, 1889.	Mercalli, September, 1888.	Judd, April, 1874.	Bornemann, 1856.	Palsterkamp, September, 1830.	Spallanzani, October, 1788.	Houel, 1776.	Hamilton, 1768.
Zolfo vent	B	A	2	B	I	2	3	3	2	IV	2	×	....	×	×	×	×	×	×
Torreone vent	C	B	4, 4*a*	C	III	6 (5)	5	5	4, 5	I	5	×	×	....	×	×	×	×	×
Sciarra vent	A	....	3	A	(II)	3	6	....	3	....	3	(×)	....	....	×	×	....	×	×
Central vents	....	C, D	5, 6, 7	E, F	....	4, 4′	4, 4′	4, 4′	....	(II, III)	4	....	....	....	....	× ?	....	× ?	× ?
Scarp vents	....	....	....	....	....	1, 1′	1, 1′	1, 1′	1	....	1	....	....	....	....	× ?	....	....	....
Fumarole vents	D	E	1	D	....	7	2	2	....	....	....	....	....	....	....	× ?	....	....	....

identity in location can have been but very small. It may be added that a slight shifting of the surface orifice may reasonably be expected above a fixed conduit that discharges through a more or less thick accumulation of loose scoria, lapilli, and ash, as would be especially true of the Sciarra vent.

Farther back on the terrace points of reference are lacking, or at least less definitely marked; yet even here we can trace back for some twenty-five years three small areas of activity which are quite persistent in their general locations. These are, of course, the Central, Scarp, and Fumarole vents. These would seem to be (at least at the surface) rather groups of vents, the individuals of which shift in number and somewhat in position from time to time, while each group occupies a rather definite and restricted area of activity.

In the case of this portion of the crater terrace it is important to remember that it has been the scene of profound changes, as in the eruption of 1907, becoming at times a large and very deep funnel, which has been subsequently filled up with loose or but slightly coherent material. The diffuse character of the surface points of discharge from single vents or conduits below through the accumulation of loose material is hence readily understandable.

We may conclude, then, that at Stromboli, for about a century and a half, at least three vents, of relatively small size (varying from 10 to 50 meters in diameter), have persisted continuously in their positions, with possibly a very slight amount of shifting, and that at other parts of the crater terrace three groups of vents have been in more or less intermittent activity, each group occupying a rather restricted area, for at least twenty-five years and probably much longer.

KILAUEA

Another volcano which offers opportunity to study the persistence of volcanic vents in location is Kilauea, by reason of the length of time that it has been observed, the series of plans and sketches made of the crater floor at different dates, and the fact that the crater topography furnishes means for the identification of location of the main focus of activity. Only a very brief statement of the main features of persistence at this volcano can be given here.

It will be recalled that the crater of Kilauea measures about 5 by 3 kilometers, with a somewhat domed floor and precipitous walls about 200 meters high. In the southwestern (the highest) part of the floor of this is a small lava pit, called Halemaumau, about 500 meters in diameter.

Since the crater was first observed by Europeans in 1823, this small lake has occupied about the same position and has been the center of activity. This is clearly shown by the series of plans and records published by Dana[33] and Brigham.[34] Dana (page 32) prefaces the record by saying: "The most active fires in 1840 were in the southwest part of the crater, as has been the fact through all the known history of Kilauea." Similarly Hitchcock[35] says: "Halemaumau is always the place where the fire may be seen. It might be called the core or nucleus of the volcano." In the eastern part of this pit is a pulsing "fountain," about 20 meters in diameter, called "Old Faithful," presumably above the narrow conduit, and of which Daly[36] remarks that it "has represented the true axis of the lava column for many years and seems to have been the main source of magmatic heat throughout the known history of Kilauea."

Here, then, we have another case of the persistence in location of a vent and conduit in a crater floor for a considerable known period of time—nearly 100 years. It is also noteworthy that, though the lavas at the two volcanoes are chemically very similar, Stromboli and Kilauea are of very different types, both in volcanic form and in mode of activity.

Etna and Vesuvius

Although the recorded descriptions, plans, and views of the craters of these two volcanoes, especially the latter, are more numerous and date farther back than is the case with Stromboli or Kilauea, yet they furnish us with little information regarding the question of the persistence of the vents. This is due partly to difficulties of observation and, as already pointed out, partly because of the approximately circular shape of the craters, their greatly varying diameters, depths, shapes, and rim outlines, so that there are no permanent points of reference by which to identify locations. In general, the only indication that can be given is reference to the compass position, and in the earlier sketches this is often rendered unavailable by neglect to state the direction of the viewpoint.

But definite cases of apparent persistence in location of vents at these volcanoes are furnished by Etna. A plan of the crater in 1897 and a photograph of it in 1901, published by Riccò,[37] show the chief active vent in the northwest sector of the crater floor close to the wall—that is, in approximately the position of one of the two vents present in July, 1914.[38]

Three sketches by M. Gemellaro, reproduced by Sartorius v. Waltershausen,[39] of the central crater at different times between 1804 and 1816 show two vents which are in fixed positions during these 13 years. The only change which they undergo is the gradual building up of a small cone about each. Neither of these appears to correspond to the vent shown by Ricco or either of those of 1914.

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[33] J. D. Dana: Characteristics of volcanoes, New York, 1890, pp. 45 ff.

[34] W. T. Brigham: Mem. Bishop Mus., vol. ii, no. 4, 1909, pp. 418 ff.

[35] C. H. Hitchcock: Hawaii and its volcanoes, Honolulu, 1911, p. 258.

[36] R. A. Daly: Igneous rocks, New York, 1914, p. 266.

[37] A. Riccò: Boll. Soc. Sism. Ital., vol. vii, 1901, fig. 5; fig. 2.

[38] Washington and Day: Bull. Geol. Soc. Am., vol. 26, 1915, p. 382, and pl. 18.

At Vesuvius there is still less evidence afforded by the plans and sketches; but some of the plans indicate the presence, fifty and more years ago, of a vent which corresponds in position approximately to that of 1914.[40]

What is probably another example of persistence of location of vents is furnished by the gigantic volcano of Tengger in Java. Here in the floor of the crater (about 25 kilometers in circumference), which resembles that of Kilauea, rise five cones, each a volcano in itself, which by their very size testify to the persistence in location of their conduits through a long period of time.

GENERAL DISCUSSION

That a vent can maintain its position on a crater floor for a very considerable period of years is at variance with some of our accepted ideas of an active volcano. Because of the profound alteration in the size, form, and depth of the crater and in the altitude and topography of the crater floor, which are so often brought about by central eruptions, we are accustomed to associate the idea of constant change rather than that of permanence with most active volcanoes, and to assume that the location of an active vent at the time of a new eruption is variable and fortuitous, though the general position of the crater may not shift.

That the foci of activity do shift position in successive eruptions is unquestionably true of those which take place on the flanks of volcanoes, as at Etna and Vesuvius. But the evidence presented in preceding pages seems to be conclusive, as far as it is available in point of time and accuracy of location, that *within the main crater,* both at Stromboli and Kilauea, and possibly at other volcanoes, a focus of activity or vent of small size may remain localized for a century or more.

That general volcanic activity may shift along a line, presumably that of a fracture in the earth's "crust," is well known, and is exemplified on a large scale by the row of volcanoes of western Italy from Bolsena to Vesuvius[41] and by the row of volcanic Hawaiian Islands.[42] With this larger phenomenon we are not here concerned; nor have we to do with the shifting of activity along a radial fissure, such as that of Mauna Loa or those of Etna.

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[39] Sartorius von Waltershausen: Der Etna, Leipzig, 1880, vol. ii, pp. 304, 305. These are reproduced by Daly, Igneous rocks, p. 143.

[40] Washington and Day: Bull. Geol. Soc. Am., vol. 26, 1915, p. 379.
A. Malladra: Boll. Soc. Geog. Ital., 1914, p. 45; Rend. Acc. Sci. Nap., 1914, p. 10.

[41] H. S. Washington: The Roman comagmatic region. Carnegie Publ. no. 57, 1906, p. 176.

[42] W. Cross: U. S. Geol. Surv., P. P. 88, 1915, p. 8.

Confining our attention chiefly to Stromboli, as this represents the more usual type of volcanic activity, and as I am personally unacquainted with Kilauea, we may examine into the cause of this persistence of a vent or vents for a considerable time at one of the halting places of the general shift and discuss briefly its bearing and that of the other features on some questions of the mechanism of volcanic action.

There is considerable vagueness in our ideas as to the conditions which obtain beneath a volcanic crater. The presence of some sort of magma reservoir seems to be a necessary assumption; but in the standard works on volcanoes and volcanism opinions either differ or are not expressed as to the depth of the top of this below the crater floor, and the origin, character, shape, and size of the conduit which connects the magma chamber with the surface. It may be added that practically all the ideal sections which have been published, not being drawn to scale (for obvious reasons), tend to give erroneous and misleading ideas of the true relations.

In general, the magma reservoir is supposed to lie at a very considerable depth (of the order of more than a kilometer) and to connect with the surface through one conduit, which is usually regarded as a local widening of the fracture line on which the volcano is supposed to stand. Very little mention is made of the size of this conduit, but it would appear that Dana's view,[43] that the area of the conduits at Kilauea and Loa is as large as or larger than that of the crater, is generally accepted as applicable to most volcanoes. Daly, on the other hand, thinks[44] that the diameter of the conduit at Kilauea and elsewhere is very small relatively to that of the crater and is of the order of magnitude of some tens of meters.

It may be said at the outset that the persistence of the Stromboli vents would seem to be best in accordance with Daly's view. Were the lava conduit of a size commensurate with the area of the crater terrace, the top of the lava column being close beneath the floor of this, one would expect vents to break out through the thin cover without regularity or continuity, at different chance points of weakness over the terrace floor at each successive eruption or accession of activity and not persist in their locations, as they have done.

On the contrary, from the persistence in location, the size, and mode of activity of the vents, we may safely draw the following conclusions:

1. The vents are the mouths or surface openings of conduits which

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[43] J. D. Dana: Characteristics of volcanoes, New York, 1890, p. 151.

[44] R. A. Daly: Igneous rocks, New York, 1914, p. 280.

have pierced through solid rock or massive beds for the greater part of their course. In the cases of the Zolfo, Sciarra, and Torreone vents the conduits must reach almost, if not quite, up to the surface. The Central, Scarp, and Fumarole groups of vents, as has been mentioned above, occupy a portion of the crater terrace which has been especially liable to profound explosive action, resulting in the occasional formation in this part of the terrace of a deep and extensive funnel, which is subsequently filled up with loose and little-compacted material. Through such an overburden the lava and its contained gases coming up from a fixed vent below would naturally tend to shift position somewhat from time to time and become at the surface a diffuse group of vents rather than a single one.

2. From the persistence in location it may be reasonably assumed that the lengths of the conduits, and consequently the depth of the top of the magma reservoir below the crater floor, must be very considerable—presumably of the order of hundreds or, more probably, thousands of meters. For, as has been stated, were the conduit of an area commensurate with that of the crater and with its top near the terrace, the volcanic activity would most presumably, in the course of a century and a half, have broken out in vents at various points on the crater terrace, instead of showing the fixity of position which we have observed. The method by which this fixity of position is maintained will be discussed later.

3. Both the persistence in location and the relatively small size of the vents, which vary in diameter from about 10 to 60 meters (the diameter of the visible orifice being almost certainly greater than that of the conduit below), as well as the persistence in small size, indicate that there has been during their existence but little melting, erosion, or assimilation of their walls by the lava and gases which have passed up through them. This lack of action on the walls of the conduit (after its formation) may be ascribed to the fact that the ascending lava, owing to the presence of gases and water vapor in solution, would have a lower fusion temperature than that of the already solidified basalt of the conduit walls, which is of about the same chemical composition, but without the gases and water vapor. Interreactions between the gases would tend to maintain the temperature and liquid condition of the lava column, but would not necessarily or probably raise its temperature above that of the fusion temperature or temperature-interval of the surrounding solid rock.[45]

In this connection it may be mentioned that the features of the vents just noted and the explanation here suggested are opposed to the idea advocated by some,[46] that a large part, if not all, of the water vapor present in lavas is derived from the wall rocks; for, apart from other considerations, the discussion of which would lead us too far afield, were the lava non-aqueous and the walls water-bearing (both being, as in this case, of essentially the same chemical composition), it is to be expected that the walls would have a lower fusion temperature than that of the lava, so that the size of the vent would be continuously enlarging.

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[45] Cf. Sosman and Merwin: Jour. Wash. Acad. Sci., vol. iii, 1913, p. 389.

[46] Cf. J. P. Iddings: The problem of volcanism, 1914, pp. 169 ff.

4. Practically all observers who have reported on the subject have noted a complete absence of synchronism in the activity of the several vents. Bergeat and Wegner have given very considerably detailed data, and their observations were fully confirmed by those of Kozu and myself. This points clearly to the independence of the several vents for a very great distance down—that is to say, it may be assumed that the conduits do not branch or diverge from a central main conduit, but that they are independently continuous down to the magma reservoir.

Another example of such independence of action is furnished by the cascades of lava which burst up through the talus surrounding Halemaumau and at considerable heights (for example, 40 feet) above its level.[47] Here we have not only independence of action, but a very distinct difference in the prevailing internal pressure. These sustained pressure differences in neighboring conduits offer unexceptionable proof of their complete independence one of another.

It will be noted that in this conclusion I differ with Perret,[48] who holds the view that the several vents are the openings of interconnected conduits, which diverge or ramify from a central one. Against this view the lack of synchronism and the different type of activity at each seem to me to be conclusive arguments.

5. Judging from the size of the vents, the diameters of the Stromboli conduits must be relatively small—that is, measurable in a few tens of meters. The diameters of the different vents vary considerably. Those of the Torreone and Zolfo have been estimated at different times and by different observers at from 20 to 100 meters, being apparently generally from 30 to 50. The Central and Fumarole vents would seem to be constantly and consistently smaller. While the diameter of the main Scarp vent, number 1 on Ricco's plans, is apparently much greater, it must be remembered that this represents not the size of the vent itself, but that of the funnel-like crater formed by its violent explosive activity, in the loose material of this part of the terrace. Presumably the mouths of the vents are somewhat larger than their conduits, because of the mechanical tearing away of the edges and walls by the explosions, though this is compensated for in part by the adhesion to the walls of the blobs thrown up

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[47] Cf. Day and Shepherd: Bull. Geol. Soc. Am., vol. 24, 1913, p. 601, and plate 26.

[48] F. A. Perret: Am. Jour. Sci., vol. xlii, 1916, p. 447.

from the boiling lava below, as was well seen by us in August, 1914, at the Torreone vent.

Examples of such narrow conduits are furnished by the pit craters which occur in Puna and elsewhere on the island of Hawaii.[49] One of these, on the slopes of Hualalai, is described by Brigham as about 25 feet in diameter, vertical, and with an estimated depth of about 1,800 feet. I am informed by Doctor Day that the walls of some of these Hawaiian pipes are glazed as by fusion.

The small size—about 10 meters in diameter—of the vent which opened in the floor of the crater of Vesuvius[50] on July 5, 1913, also indicates that its conduit is of similar order of magnitude.

Before discussing the origin of these vents their situation must be described, as it has an important bearing on the problem. The present crater terrace represents a late site of activity within an earlier and larger crater, the remains of which are seen in the Serra Vancori to the south and ridges to the northeast and southwest. The relations are much like those of Vesuvius and Somma, but on a smaller scale. The present crater differs, however, from Vesuvius and nearly all other similar intrasommal craters or cones in being asymmetrical. The northwest side plunges steeply down to the sea in the so-called Sciarra.

This peculiar configuration has been variously interpreted, as is brought out by the discussion of Bergeat. With him we may dismiss the ideas that the Sciarra represents the original Vancori crater (as it may be called), or that it is an erosion valley, or Scrope's suggestion that it is due to an explosion which blew off half the old Vancori cone. The explanation of Bergeat,[51] that it is due to faulting and subsequent subsidence of a block on the northwest, is the most rational one.

Although not mentioned by Bergeat, the submarine contour lines lend strong probability to this view. As seen on a hydrographic chart, or even as shown on Bergeat's small scale map (plate II), the gradient of the sea-bottom is far steeper on the northwest side of the island (that is, along the Sciarra) than elsewhere, and very close to the shore becomes almost precipitous. It may be added that this line of sharp declivity is continued along the whole northwest edge of the Æolian Islands as far as Alicudi.

But, whatever be the cause of the disappearance of the northwestern part of the old Vancori cone, we may reasonably suppose that the Sciarra is merely a talus heap, made up of the material ejected from the vents above, and covering and masking a more or less precipitous scarp approximately below its upper edge.

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[49] W. T. Brigham: Mem. Bishop Mus., vol. ii, 1909, pp. 11, 97.

[50] A. Malladra: Rend. Accad. Sci. Nap., 1914, p. 10; Boll. Soc. Geog., 1914, pp. 45 ff. Washington and Day: Bull. Geol. Soc. Am., vol. 26, 1915, p. 379.

[51] Bergeat: Op. cit., p. 27.

We have, then, the vents opening from presumably long and narrow conduits very close to the edge of a more or less nearly vertical scarp, about 700 meters above sealevel. They may occupy the site of the former Vancori focus of activity; but, from consideration of the configuration and topography of the remains of the earlier cone, and from analogy with other volcanoes, it is most reasonable to suppose that the chief center of activity has shifted slightly to the southeast, and that the vents have opened on the terrace subsequent to the subsidence of the northwest portion of the old Vancori cone.

In this respect their situation is strikingly like that of some of the small secondary or parasitic vents of Etna, which have opened very close to the edge of the scarp that bounds the great caldera of the Val del Bove. This scarp is almost precipitous (except for talus and ash) and attains a height of some 2,000 meters. Of these vents may be mentioned Montagnola, Cisterna, and Renato. It is to be noted that all these are of recent dates, long subsequent to the formation of the Val del Bove; and also that the walls of this are built up of beds of lava and of somewhat compacted agglomerate.

A similar occurrence is the outbreak of lava in 1832 near the center of the ridge which separates the crater pits of Kilauea and Kilaueaiki,[52] the streams of which flowed down both sides of the ridge, called Byrons Ledge.

The main characters of the Stromboli vents whose origin we desire to explain are these:

1. Their persistence in location for a very considerable time.
2. Their considerable number (6) and contiguity (in spite of their permanence) over a restricted area (about .5 kilometer square).
3. The want of synchronism and difference in type of volcanic activity and the consequently deduced non-connection of their conduits.
4. Their small size and the consequently presumably small diameter of their conduits.
5. The presumably very considerable depth (of the order of several kilometers) to which their conduits extend.
6. Their situation near the edge of a scarp about 700 meters high.

Taking these characters into consideration, it is clear that no origin based on explosive agencies can be postulated—that is, the Stromboli vents can not be "explosion diatremes"—in the sense of Daubrée and Daly,[53] though other volcanic vents may be and are of this type. Their number and contiguity on the terrace (2), the lack of synchronism (3), their small size (4), the presumably great depth of their conduits (5), and, above all, their situation near the edge of a scarp (6), all negative such an origin. Any explosive action sufficient to establish connection between the assumed magma reservoir and the surface could not permit of the formation of a number of small conduits close to each other, with non-synchronic activity, and situated close to a scarp, through the face of which, with its many planes of weakness, any such activity would most easily find outlet.

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[52] W. T. Brigham: Mem. Bishop Mus., vol. ii, 1909, pp. 46 and 90.
C. H. Hitchcock: Hawaii and its volcanoes, Honolulu, 1911, p. 183.

[53] R. A. Daly: Igneous rocks, 1914, p. 252.

To account for such a combination of characters as the Stromboli vents present, there must be invoked an agency or mode of action that is at once quiet, but effective in penetrating the overlying masses; with not only preponderatingly, but essentially, vertical direction of action, and with but limited lateral extension: with the possibility of action at several points in close contiguity and without mutual connection near the surface, and, finally, the possibility of the continuance of the conduits and the activity of their vents in the same locations during a considerable period of time.

The only agency which seems competent to satisfy all these (somewhat complex and difficult) conditions is that suggested by Daly[54] in his "gas-fluxing" hypothesis. Indeed, so difficult is it to account for the characters and situations of the Stromboli vents, and also for the situation of the vents on the brink of the Val del Bove scarp and Byron's Ledge at Kilauea by any agency that involves extensive or violent explosive action or fracturing at depth, that the formation and existence of such vents must be considered as not only confirmatory of, but as demonstrative of, the validity of such a theory as Daly's in these cases, and presumably in others, though of course not necessarily in all.

Briefly put, Daly's hypothesis is as follows: Gas bubbles rise in the magma to the top of the assumed reservoir and accumulate in pocket-like irregularities ("cupolas") in the roof. They are supposed to be more highly heated than the magma itself, chiefly through exothermic chemical reactions, and thus melt or "blow-pipe" their way up through the superjacent rock. This action is sharply localized by beginning in greatest intensity at one or several cupolas, will be predominantly vertical in direction, and "the size (of conduit) will be small because the fusing power of emanating gas must be strictly limited." Thus more than one conduit may be formed which will be independent one of another. After a conduit has been formed, it will tend to persist as long as there is a supply of gas.

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[54] **R. A. Daly: Igneous rocks, 1914, pp. 251 ff.**

The evolution of heat through the chemical interreactions of magmatic gases and their consequent competence to "blow-pipe" their way, and thus form a conduit, to the surface has also been suggested and discussed by Day and Shepherd.[55]

Daly applies this action to the revival of activity after a period of dormancy. He supposes that the gas "blow-pipe" melts its way up through the solidified plug which fills and obstructs the conduit (figure 135, page 276). But it may be pointed out that as this plug will consist of very solid and tough rock, as he himself says, the vertical fluxing action would probably take place not through, but alongside, of the plug, thus slightly shifting the vent at the surface. If, however, the conduit remains open, or only slightly obstructed, or if the solid plug be not too long, the exact location of the vent will persist.

It will be noted that certain important features of such a "gas-fluxing" process are its quietness of operation, the boring being due to simple fusion and not to explosion (except when the surface is reached); the dominantly vertical direction and slight lateral extension of action; the localization and independence of the several bore holes (if there are more than one), due to their initiation at separate cupolas; and the possibility, by continuance of this action, of the persistence in location of the vent.

These features fully meet the requirements of the characters of the Stromboli and Etna vents, and so it must be regarded that the "gas-fluxing" hypothesis of Daly is competent to explain their origin, characters, and (at Stromboli and Kilauea) their persistence in location.

This hypothesis is especially well fitted to explain the formation of the vents on the Stromboli crater terrace, if it be true, as seems most probable, that this occupies the top of an unsunken portion of the earlier Vancori cone, back of a steep fault-scarp. It would be precisely under this portion of the mass, after the subsidence of the northwestern fault-block, that the magma reservoir would be expected to preserve its original upper level, so that this portion would serve as a locus of accumulation for the magmatic gases. It is conceivable, also, that the number of vents and their contiguity over a comparatively small area is due to the same cause and the consequent areal restriction of the reservoir roof without commensurate diminution of the gas supply.

It may be added that the applicability of the gas-fluxing hypothesis to Stromboli has indeed been suggested by Daly (op. cit., page 268); but he would seem, possibly through lack of acquaintance with the volcano, to have misunderstood the character of its crater terrace and to have overlooked the features of its vents, as well as those of the Etna ones mentioned, which tell most strongly in favor of his own hypothesis.

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[55] Day and Shepherd: Op. cit., pp. 599-601.

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POST-GLACIAL MARINE SUBMERGENCE OF LONG ISLAND[1]

BY HERMAN L. FAIRCHILD

(Presented before the Society December 28, 1916)

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INTRODUCTION

Perhaps more than any other equal area in America, Long Island has been the subject of indecisive geologic study and lively disputation. For over a century it has afforded the students of stratigraphic and surficial geology an opportunity for difficult diagnosis, and the complex features have been attacked from every position of geologic philosophy. But the problem has outrun the investigation. The preglacial deposits are thought to have been overridden, disturbed, and confused by the recurrent ice-sheets, and much remains to be determined with reference to correlation of strata, the origin of the island, the amount of Pleistocene movement, and the genesis of the topography.

---

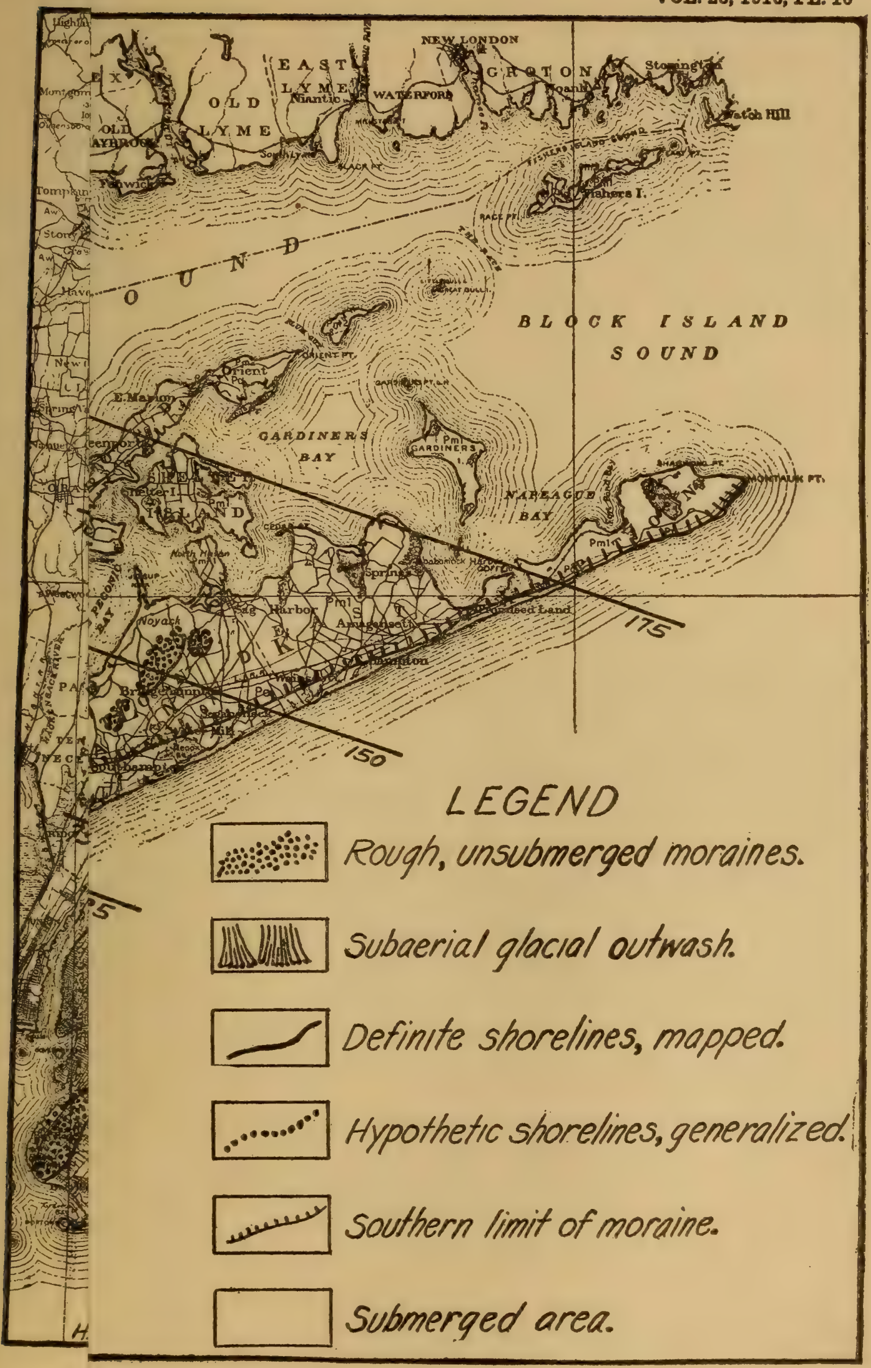
[1] Manuscript received by the Secretary of the Society December 26, 1916.

The most conspicuous topographic features of the island, which have naturally received most attention, are the belts of morainic hills. But quite as interesting and of equal significance are the extensive sand-plains, equivocal in their origin. The present paper will present the facts which prove that the southern and the eastern plains were formed as a submerged marine plain. The bearing of some of the phenomena on the genesis of the plain has not been recognized and the many evidences of submergence have never been assembled.

The writer's interest in Long Island is not simply because the area has had a salt-water bath, but because the submergence was part of the very recent diastrophic movement of northeastern America, which has not been recognized in its full value.

This paper is not an argument against any apparently contradictory facts nor against any preponderance of opinion or weight of authority, because no facts to disprove Post-Glacial submergence have been presented, and the weight of geologic opinion favors at least some lower attitude than the present. It is true that a few recent writers have assumed or asserted an elevated attitude of the island when the latest deposits were made, but without meeting the positive evidence presented by earlier writers of the lower attitude of at least the west end of the island and without making any allowance for the depressing effect of the weight of the latest ice-body. It is unnecessary to enter into any discussion of the very complex history and involved glacial deposits as postulated by Veatch (25) and Fuller (27), for the evidence of Post-Wisconsin submergence can stand alone.

Although it is here claimed that the combination of characters in the plains can be fully explained only by the theory of immersion, the proofs of Post-Glacial submergence of Long Island, to the extent indicated in the map (plate 10), which are relied on in this writing, are quite independent of the characters of the plains in the central and western parts of the island. The convincing evidence of the submergence is found in the combination of elements and features which have been overlooked or their significance not recognized in this connection. These are (1) the fact that the island lies well within the area of Post-Glacial depression; (2) the positive evidence of deep submergence of the near-by Hudson Valley and the Connecticut Valley (28); (3) the subdued, wave-washed surface of the moraines below the theoretic plane, and the very rough, harsh, unsubdued aspect of the moraines above that plane; (4) the presence of


NEW LONDON
EAST LYME
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WATERFORD
GROTON
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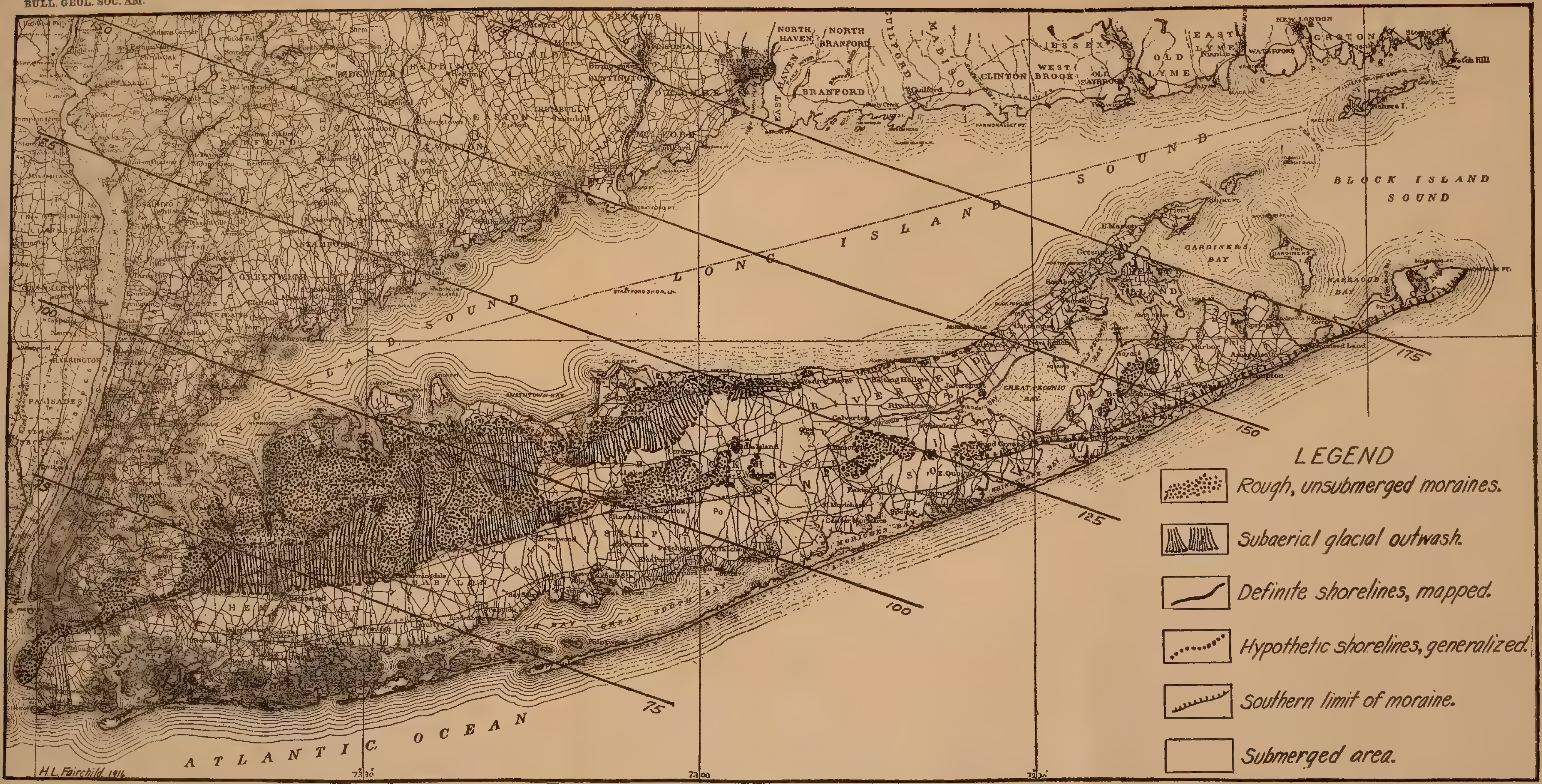
Watch Hill
OLD LYME
OLD SAYBROOK
Fenwick
Fishers I.
SOUND
BLOCK ISLAND SOUND
Orient Pt.
E. Marion
Greenport
GARDINERS BAY
GARDINERS
Pml
Shelter I.
ISLAND
NAPEAGUE BAY
Montauk Pt.
Springs
Sag Harbor
Amagansett
Promised Land
Noyack
Bridgehampton
Southampton
PECONIC BAY
175
150
75
LEGEND
Rough, unsubmerged moraines.
Subaerial glacial outwash.
Definite shorelines, mapped.
Hypothetic shorelines, generalized.
Southern limit of moraine.
Submerged area.


LEGEND
Rough, unsubmerged moraines.
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Southern limit of moraine.
Submerged area.
LONG ISLAND SOUND
BLOCK ISLAND SOUND
GARDINERS BAY
GREAT PECONIC BAY
GREAT SOUTH BAY
MORICHES BAY
SMITHTOWN BAY
ATLANTIC OCEAN
NEW HAVEN
NEW LONDON
RIVERHEAD
ISLIP
BABYLON
HEMPSTEAD
75
100
125
150
175
H.L. Fairchild 1916.
73°30'
73°00'
72°30'

POST-GLACIAL MARINE SUBMERGENCE OF LONG ISLAND

innumerable kettles in the smooth eastern plains, proving the subjugation by standing water of ice-laid drift; (5) the occurrence of surficial loams over large tracts of the lower plains; (6) the admitted delta terraces or sand-plains on the north side of the island and north side of the latest moraine, at the theoretic height (21, pages 653-654); (7) the occurrence of fine, evenly bedded sands containing rafted boulders in the moraine valleys; (8) the evident shorelines about the eastern moraines and the wave-erosion origin of the "Inland Cliff." These features will be separately discussed in a later chapter.

The principal facts which have been noted as unfavorable to recent submergence are negative in character. These are the absence of beaches, bars, or cliffs on the surface of the plains and the absence of fossils. To these objections there are conclusive answers, which will be stated in a later chapter.

HISTORICAL REVIEW

In 1908 M. S. Fuller, in the most exhaustive paper on the geology of the island (see number 26 of the bibliography), gave an excellent review of the literature relating to the geology from 1750 to 1908. A reference to that paper will show that most earlier students of the island believed the southern plain was formed beneath the sea and, as the present writer thinks, correctly.

It is an interesting fact that the earliest writing on Long Island of which we have record (1, page 150) recognized marine submergence. Mather gives the following translation of de Nemour's writing:

> ". . . says of Long Island, that although not a delta in form, is one in reality, caused by the marine currents transporting the fluviatile alluvions of the Hudson, Passaic, Hackensack, and Raritan rivers."

For that early time, so long before the discovery of glacial agency, it was a much more rational conception than the cataclysmic notions of the drift commonly held in Mather's day.

The earliest published article relating wholly to the plain was in 1859, by W. C. Watson (2), not geologic, but a description of the plains with reference to their agricultural possibilities. However, he noted some of the features which have a bearing on the genesis of the plain, and while perhaps too vague and broad his statements have much value as the observations of a keen observer with no geologic bias. His only definite statement as to the origin of the plain is this: "Submergence of the island at some period is demonstrated by numerous circumstances" (page 487). He speaks of marine shells being found in the plain and in the channels or "dry rivers." His remarks concerning these channels, the surface soils, the absence of stones, the flatness of the plain, and other points will be quoted later.

Many articles after 1859 relate to the geology of Long Island, but without any important reference to the plain. In 1877 Elias Lewis, Jr., published several articles, three of which are here listed (3, 4, 5). He also affirmed submergence of the island, but did not discriminate between the ocean-laid deposits and the glacial gravels, as he postulates submergence to height of 260 feet (3, page 145). He says that marine shells had been found up to 200 feet, but they must have been, like beach deposits of shells seen today, pushed up by the ice-front. His paper on the watercourses will be treated later.

From 1877 to the present time no geologist, so far as the writer knows, has directly and unequivocally affirmed the subaqueous origin of the Long Island plain in its entire length, though several have stated or implied the opposite. In 1890 F. J. H. Merrill claimed marine submergence for the west end of the island, and J. B. Woodworth, in 1901, was willing to concede submergence of 40 feet over the west end of the island and came very near to recognizing the full 80 feet.

The first clean-cut affirmation and description of the uplifted marine plain in the vicinity of New York, with precise data and altitudes, was by Merrill in 1890 (10). The papers by Heinrich Ries on the Pleistocene clays of the Hudson Valley (12-15) proved their estuarine origin and the submergence of the region. W. M. Davis, in 1892, clearly recognized the Hudson estuary and described delta features at Catskill (16). Two articles by N. H. Darton, in 1894 (18-19), also recognized the estuarine character of the Hudson deposits. Quotations from these writers will appear later in this paper.

From 1894 to 1901, as in previous years, the complex of glacial and preglacial deposits in the morainal belt and north side of the island received much attention, but no special study was given to the problem of large Post-Glacial uplift of the region. The positive evidence given by Merrill, Ries, Davis, and Darton was apparently ignored, and the subaerial outwash origin of the entire plain seems to have been assumed. In 1901 Woodworth published his study of Nassau County and the Borough of Queens, which was the first paper to differentiate, locate, and map the drift deposits, specially of the west end of the island, instead of resting in general description. In this discriminative paper (21) Woodworth noted many features which are due to submergence and recognized their suggestion. He admitted the shorelike character of the inner edge of the plain and described deltas that were proof of standing water at Port Washington and Great Neck, with altitude of 80 feet. But after some argument he ruled out the sea as the formative water body for the deltas, chiefly because the inner margin of the frontal plain did not everywhere accord in height with the deltas (645-650). We now see that such accordance is not to be expected, as the uplift has a tilt of about 1.25 feet per mile in direction parallel to the face of the moraine in that district. He explained the 80-foot terraces by glacial waters, but the lower features were too wide-spread for such explanation, and he wrote as follows:

> "As for the possibility of the 40-foot delta at College Point having been deposited at sealevel, it should be stated that similar formations north of the moraine indicate wide-spread waters at about this level. When these have been fully investigated, it may be necessary to admit a submergence to this extent. What is stated here must be taken with this reservation in mind" (page 658).

A glance at the map, plate 10, will show that the features and altitudes which Woodworth notes are all in perfect harmony with the uplifted and tilted marine plain, and that the higher levels represent the theoretic summit. Woodworth recognized the slope of the country. He says, page 644:

> "Just as the level of the deposits fall off on the north side of the moraine to the westward, so does the height of the outwash plain and, for that matter, that of the moraine itself."

And on page 646:

> "The line of contact with the moraines gradually rises from west to east, very much as the elevation of the older Pleistocene increases on the north of the moraine. Everywhere the plain appears to rise continuously to the base of the moraines."

This important character of the plain is described later, page 293.

In 1902 R. D. Salisbury published the summation of his extended and critical studies on the Pleistocene of New Jersey, which necessarily had to include Staten Island and the west end of Long Island. In the New York City Folio (23) he described the coastal plain features of Staten Island and western Long Island and found no explanation except marine submergence; but on account of the lack of distinct beaches and marine fossils he did not make positive assertion of submergence. But in the report on the glacial geology of New Jersey (24) he described a multitude of features which indicated standing water and distinctly favored the view that New Jersey had been submerged since the ice withdrawal to a depth of 100 feet on the north boundary of the State and about 40 feet in the southern part of the State (24, pages 196-213, 508-513).

The two most elaborate treatises on Long Island geology are by A. C. Veatch and others on the underground water resources, in 1906 (25), and by M. L. Fuller, in 1914, on the geology of the island (27), both papers being Professional Papers of the United States Geological Survey. Both of these writings held the view of subaerial glacial outwash for the genesis of the plain, but without any adequate evidence or argument. It was simply assumed without discussion as an element in their philosophy of the complex history. It is somewhat surprising that the mass of facts presented by such able men as Merrill, Ries, Davis, Darton, Salisbury, and Woodworth should be entirely ignored, even though the evidence was mainly at the west end of the island. Fuller admitted a depression of 20 feet on the New Jersey coast, but says it was not recorded on Long Island.

Since 1913 the writer has maintained the marine origin of the high level terraces in the Hudson and Champlain valleys, and has shown in maps the probable glacial depression of New York and New England. The New England geologists have long recognized, but quite certainly underestimated in amount, the Post-Glacial submergence of the Massachusetts coast and the maritime provinces of Canada. The larger treatment of this subject will have to include all the glaciated territory, for it becomes more and more evident that the ice-cap weighted down the area which it occupied.

Description of the Plain

For a brief general description of the Long Island plain in its geologic characters we can not do better than to quote from Salisbury (22, page 14), preceding his description of the plain by one of the Staten Island lowland, similar in features and identical in origin to that of Long Island. But it should be said that these descriptions do not apply to the smooth plains with numerous kettles at the east end of the island.

"*Staten Island.*—The considerable plain of stratified drift which skirts the moraine of Staten Island on the south, between Fort Tompkins and Great Kills, has a gentle slope seaward, and ends in a marsh which is shut in at the south by the beach ridge of recent origin. The greatest width of the plain, near New Dorp, is about 1½ miles. The plain was contemporaneous in origin with the terminal moraine, the materials of which it is composed having been washed out from the edge of the ice when the moraine was being deposited. At its moraine edge the plain is made up of coarse gravel, but with increasing distance from the moraine the material becomes finer, grading off into sand. The sand and gravel of the plain are often covered with clay loam, so that the coarser materials below are shown only in excavations. The depth of the stratified drift is unknown, but it is known to exceed 30 and 40 feet at many points, and its base is therefore often below sealevel.

"The plain is one which might give rise to various interpretations. It has not the even slope away from the moraine which is characteristic of overwash plains. It is not unusual for such plains to have some undulations near their moraine edges; but in this case the undulations are often conspicuous half a mile from the moraine, the depressions being such as to occasion swamps and even ponds. Again, the surface of the plain is covered with several feet of clay loam, often stiff enough for brick clay. This is like the loam over the moraine near the west end of the island and perhaps at other points. The disposition of the drift south of the driftless area near New Dorp is not exactly what would have been expected if it were deposited by running water. Though in these minor particulars this plain departs somewhat from the normal outwash plain, the departures are so slight as not to negative the conclusion that such was its origin. They are enough, however, to raise the query whether the plain has not been submerged to the extent of 40 feet or so since the ice departed. Against this view stands the fact that distinct shore features are absent. To suppose that it has been submerged is to suppose that the submergence and subsequent emergence were accomplished without the development of distinct shore features, such as beach lines, spits, or cliffs."

"*Long Island.*—The moraine in the Brooklyn quadrangle is everywhere bordered on the south by a plain of stratified drift. It slopes away from the moraine, at first more steeply and then more gently. Its decline in the first quarter of a mile is often as much as 20 feet, and a further decline of an equal amount is accomplished in another mile. The moraine edge of the plain has an elevation varying from 20 to 80 feet, but most commonly between 60 and 80 feet. So distinct is the line of junction of plain and moraine that it has sometimes been interpreted as a shoreline; but the line departs too much from horizontality to bear this interpretation, unless indeed it has undergone notable deformation since its development. . . .

"Like the corresponding plain on Staten Island, this also departs in some respects from the normal outwash plain. The surface of the plain is somewhat uneven. Elevations are less common than depressions, but neither is confined to the moraine edge of the plain. . . . Another peculiar feature is certain rather notable valleys and valley-like depressions which do not appear to be utilized by drainage at the present time. Some of them may perhaps have been developed by normal drainage before the cultivation of the land, but others are closed at both ends. The topography of this plain raises the same questions as that of Staten Island."

The reader will note that Salisbury evidently favors the idea of submergence to account for the characters of both the Staten Island and Long Island plains, but is cautiously non-committal on account of the absence of definite shore structures. The lack of bars, etcetera, was the chief negative fact. The same difficulty was found by Shaler in his study of the plains of Marthas Vineyard and Nantucket (see page 300). This defect in the marine record will be satisfactorily explained in a later chapter (page 299).

The lack of horizontality or the deformation of the inner edge of the plain, the evident shoreline, is exactly what is required by the tilting uplift of the region, clearly shown in the accompanying map of isobases, plate 10.

All the existing or positive features of both plains are just those which should be expected in a glacial outwash laid down under the sea. The important characters, specially the equivocal ones, will be considered in the later chapters.

SUBAERIAL OUTWASH

The diversity of view and the failure of some students of Long Island geology to recognize the evidences of submergence may be partly due to their theories of elevation, but is also explained by the dual character of the plain. The later geologists, making more detailed study of the complex morainal tracts, approached the plain from the viewpoint of the moraines, and naturally emphasized the outwash origin of the plain, which is the true genesis of some portions of the higher plain, where it laps on the moraines. The absence of any clear line of demarkation between the subaerial and the subaqueous belts encouraged the view of subaerial outwash for the entire breadth of the plain.

The writer concedes that some portions of the plain were built by the glacial outwash above the reach of the sea. On the map (plate 10) an attempt is made to indicate these areas, which show more clearly on a large map of the assembled topographic sheets.

The areas of the plain which appear to have been built seaward, so as to fill the shallow waters and exclude the sea, lie north of a line connecting the villages of Queens, Hempstead, Deer Park, Brentwood, and Ronkonkoma. From Farmingdale eastward the railroad lies on the marine plain. The most extensive single area of subaerial outwash is the district of New Hyde Park, Mineola, Hempstead, and Hicksville (Oyster Bay and Hempstead quadrangles). Smaller areas lie between the detached moraine masses, as follows: A strip between the Bethpage Hills and Half Hollow Hills, or northeast of Farmingdale; north of Deer Park and Brentwood; between the southern and the northern moraines, the district of Greenlawn, Larkfield, and Commack (Northport quadrangle), and a belt facing the northern moraine between Smithtown and Rocky Point (chiefly on the Setauket quadrangle).

East of Yaphank, along the earlier (southern) moraine, and east of Wading River, along the later moraine, there are no subaerial outwash plains. All the plains in the eastern half of the island were wave-leveled, and only the higher parts of the moraines stood above the sea.

The stronger lobations of the outwash have some relation to the breaks in the moraines or the channels which were the exit of heavy drainage, as noted by Woodworth.

The line of contact between moraine and wave-smoothed gravel plain is a good shoreline west of Jamaica that has long been noted and questioned. Eastward the shore is very clear at Farmingdale; also on the moraine hills north of Eastport and East Quogue, and specially clear northwest of Bridgehampton.

The lack of distinct shorelines between the submerged and the exposed portions of the sand-plain is doubtless the reason why later geologists found no genetic distinction between the higher and lower belts of the plain. but regarded the whole plain as subaerial outwash. But this lack of distinct beaches on the surface of the sand-plain is not a valid argument against submergence. On the contrary, it is the natural condition when all the various factors are considered. The land was rising and the zone of wave-work was steadily falling. The waters lapping on the gently sloping sand-plain were subject to considerable variation of level. In addition to the tidal fluctuation, there is to be added the lifting or depressing of the water level by severe storms. This vertical range may well have been 10 to 15 or possibly 20 feet, which would give a horizontal range of the water on the low gradient plain of at least one or two miles. Bars are usually weak or absent on plains of sand or fine gravel, the reason for which is given later (page 300).

It should be noted that both Salisbury and Woodworth have written that the Long Island plain did not exhibit the normal features of subaerial outwash. The drainage is too well distributed; the channels are not on the apexes or crests of the swells or "fans," but between the broad, flat areas. The lobations are too broad and flat for glacial stream deltas, and the channels are too indefinite and fail in continuity. There is a remarkable lack of coarse materials on the swells and even along the creases or so-called channels.

Any one inclined to insist on the subaerial origin of all the plain should answer these questions: Can any plain with similar topography be found anywhere along the whole extent of the terminal moraine, unless where clearly faced by standing water? Is it really possible for alluvial fans, built of the coarse materials swept out of the ice-front, to unite and blend together so as to produce such continuous, smooth plains? Is it likely that streams draining the ice-sheet were ever so evenly spaced and so equal in volume as to produce such level plains?

The stronger or more definite channels are above the theoretic marine level. A good example is seen northeast of Farmingdale, along the east side of the West Hills; between the moraines, west of Dix Hills; one leading from Commack to Edgewood, and through the later moraine from Brooklyn to Roslyn, as noted by Woodworth. Some allowance must be made for storm wash and stream-work since the land uplift; but this is more noticeable along the outer border of the plain, which lay in deeper water and where in consequence the surface soils are more clayey and more subject to erosion. Most of the creases or hollows along the inner margin of the submerged belt have the characters produced by offshore currents from streams and from tidal scour. They will be discussed later.

In summation of this chapter it may be said that the characters of the plain are such as should be expected under the condition of partial submergence.

THE SUBMARINE PLAIN

The portion of the great plain which lay under the sea constitutes the belt along tide water from Brooklyn city to Yaphank, about five or six miles in width, and all of the east end of the island east of the meridian of Yaphank except small areas of the higher moraine hills on the Riverhead and Sag harbor quadrangles; also it apparently included an irregular, narrow strip on the Setauket quadrangle east of Smithtown, lying between the two moraines, which the outwash from the second moraine did not entirely fill.

The surface characters of the western sand-plains have already been described in the two preceding chapters. The plains at Riverhead and eastward are quite different, but they will be described in a later section under the term kettle plains.

The features pertaining to at least the west end of the island have not been convincing to all observers of the submarine origin. In the genetic interpretation of many geologic phenomena there enters a large psychologic factor, and the mental prepossession or working theory is often the determining force. "We see that for which we are looking." Physiographic features seem to be especially susceptible to varied interpretation. To the writer the very smooth, even sand-plains, considered alone, are clear evidence of standing water. Other students with a different philosophy of the history find subaerial origin for the plains. It would seem as if an intensive study of the plains ought, by itself, to prove the genesis. But it may be repeated that the evidences of Post-Glacial submergence emphasized in this paper are quite independent of the argument from the characters of the sand-plains.

PROOFS OF SUBMERGENCE

EVIDENCE FROM THE HUDSON VALLEY

Unless some unusual faulting or other very localized movement is postulated for the Hudson Valley, it must be apparent that considerable diastrophic movement of that valley must involve neighboring territory and at least the west end of Long Island. The reader will admit that if it can be clearly shown that the lower Hudson Valley at the time of the removal of the latest ice-sheet stood at least 100 feet below its present attitude, then at least the west portion of Long Island must have been involved in the submergence and subsequent uplift. And the proofs for the Hudson Valley are incontrovertible. All students of the Post-Glacial deposits of the valley agree that they are estaurine. We will listen to the testimony of several eminent authorities.

In 1891 F. J. H. Merrill wrote as follows (11, pages 103-106):

"These deposits are of two general types: estuary formations of stratified clay and fine sand deposited in still water and cross-bedded delta deposits of coarser material. They fringe the river shores in terraces between New York and Albany and indicate a long period of submergence, their present altitude above tide showing that the land has been elevated with respect to sealevel since their formation. Their materials were apparently brought into the estuary by tributary streams which dropped the coarsest particles near their mouths, while the finer rock-flour was carried on in a state of suspension, and was finally precipitated to form beds of clay.

"The estuary deposits of the Hudson River at New York indicate a post-glacial depression of more than 70 feet. The terraces which border the west shore of Manhattan Island from Seventy-fifth street northward have a maximum height of 70 to 75 feet, and on the New Jersey shore of the river terraces of about the same altitude occur at frequent intervals. One of the most prominent of these is at Fort Lee, south of the steamboat landing. The surface material of these terraces is a fine sand or silt easily transported by the wind. It is evidently not a material which could be laid down in running water, for it would be carried in suspension by a river current and could only be precipitated in the still water of an estuary. . . .

"On the Long Island shore of Westchester County, New York, the till which covers the metamorphic rocks has apparently been leveled off by wave action at an altitude of 75 to 85 feet. Plains of this character occur at frequent intervals, being separated by river valleys, and were probably formed during the depression which occasioned the estuary deposits of the Hudson River valley. These plains are composed of a modified till, obscurely stratified, somewhat sandy near the surface and comparatively free from boulders, but unaltered boulder-clay or till occurs a few feet below their surface. On one of the most extensive of them the village of New Rochelle is built. . . .

"From the evidence quoted the amount of the post-glacial depression at New York is estimated at about 80 feet. . . .

"In the estuary which occupied the Hudson River valley during the depression there was deposited a great depth of plastic clay, evidently a sediment of aluminous rock-flour produced by glacial attrition, and held in suspension by the post-glacial streams, and resting on this clay is a deposit of fine stratified sand." . . .

In his book on the clays of New York, Ries introduces his description of the clays in the Hudson Valley as follows (15, page 576):

> "Among the most extensive and important clay formations occurring in New York are those of the Hudson Valley. Here are deposits of two types: (1) Estuary deposits of fine stratified sand, yellow and blue clay, and (2) cross-bedded delta deposits, the materials of which are much coarser. The estuary deposits indicate a period of depression and deposition in quiet water. The clay is chiefly blue, but where the overlying sand is wanting or is of slight thickness it is weathered to yellow, this weathering often extending to a depth of 15 feet below the surface, and to a still greater depth along the line of fissures through which the waters can percolate. The depth of oxidation is of course influenced by the nature of the clay, the upper portion weathering easily on account of its more sandy nature and hence looser texture. Horizontal stratification is marked and the layers of clay are separated by extremely thin laminæ of sand. At some localities the layers of the clay are very thin and alternate with equally thin layers of sandy clay. This condition is found at Haverstraw, Croton, Dutchess Junction, Stonypoint, Fishkill, Cornwall, New Windsor, Catskill, and Port Ewen. At all of the above mentioned localities except the last two the clay is overlain by the delta deposits of rivers tributary to the Hudson, and the alternation of layers may be due to variations in the flow of the rivers emptying at those points, the sandy layers being deposited during periods of floods. . . . Isolated ice-scratched boulders are not uncommonly found in the clay.
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> ". . . Of the blue and the yellow clay the former is the more plastic, but both effervesce readily with acid, due to the presence of 3 per cent to 6 per cent of carbonate of lime and are therefore, properly speaking, marly clays."

In his detailed description of the clay banks, Ries makes frequent mention of glaciated boulders in the clay, some of them being several feet in diameter.

W. M. Davis, in 1892 (16), published an admirable description and discussion of Catskill delta features built in the Hudson estuary, clearly recognizing that the "Champlain submergence" involved the Hudson Valley. He found the amount of submergence, as registered by the cobble deltas in the Catskill Valley in the district of South Cairo, to be 270 to 280 feet. Our figure for the theoretic marine plain, as shown in plate 10, is 270 to 275 feet. And it may be noted, as added confirmation of these figures, that nine miles eastward, across the Hudson Valley, is a splendid gravel bar, a mile south of Hudson City, on the same isobase as the deltas described by Davis, with altitude approximately 275 feet.

Baron Gerard de Geer published, in 1892 (17), the results of his reconnaissance work in eastern America bearing on Pleistocene changes of level. Failing to discover distinct beach phenomena and not recognizing the equal importance of postglacial deposits in the valleys, he concluded that the submergence was very slight along the coast, and drew his isobase of zero at New York City and northeast through Connecticut and Massachusetts (plate 13, facing page 464).

De Geer saw some of the heavy beach features in the Champlain Valley, but failed, like most observers, to determine the summit level. Saint Albans, Vermont, he gives as 658 feet. The true figures are 740 feet.

N. H. Darton, in 1894, describing the geology of Albany and Ulster counties, also recognized the estuarine origin of the Hudson Valley clays and sands (18):

> "The stratified sands and clays occupy the great plain of the Hudson and Mohawk valleys. The clays are the basal member and the sands cap them to a greater or less thickness. . . . They lie on glacial drift, for the most part of no great thickness, and on the glaciated surface of the Hudson River shales and sandstones. Both the underlying drift and rocks extend to the surface in some localities as islands where the clays and sands were deposited around them. These clays and sands were deposited in the Champlain period, which followed the last glacial invasion of the region. This period was one of submergence, in which the waters of the Hudson and Mohawk rivers extended far above their present levels and overflowed all the country west to the Helderberg escarpment or the hills adjoining it to the east and north. . . . To the northward there were open waters to Lake George and Lake Champlain over a wide area" (page 260).
>
> ". . . The clays and sands constitute a terrace of varying width bordering the Hudson River. . . . They are the products of a submergence at the close of the Glacial epoch, which is known as the Champlain period. During this submergence the waters of the Hudson extended over the area now occupied by the deposits, which have since been elevated and cut into by the present drainage.
>
> "These deposits extend up to an altitude averaging about 250 feet to the westward and to considerably less along the Hudson. They consist normally of a clay deposit below overlaid to a greater or less thickness by sand. At points where the streams entered the submerged area at the time of the deposition of these deposits there are also found delta deposits of coarser materials. The clays lie on thin, irregular masses of glacial sands and gravels or on glaciated surfaces of rocks" (19, page 369).

Several years of close study by the writer of the terraces and shore phenomena in the Hudson-Champlain Valley fully confirms the testimony of the earlier geologists. Practically continuous and conspicuous evidences of standing water extend up the Hudson-Champlain, rising from 120 feet above tide at Croton Point to 800 feet in Vermont. This is not a theory, but a fact, open to any one with eyes to see plain shore features. Now, the waters were either oceanic—that is, sealevel or confluent with the sea—or they were glacial. A little fair consideration of the factors involved will positively rule out glacial waters. The waters were deep and long-lived. No morainal drift barrier could stand up for any time against the heavy outflow; for after the ice-front had receded as far north as Albany all the drainage now carried by the Saint Lawrence, augmented by the flood from the melting ice-sheet, passed out through the Hudson Valley. The writer knows of no glacial water of any size and length of life held up by a morainal dam.

The only sites which can be suggested for a drift dam are at the terminal moraine (the Staten Island Narrows) or in the constriction of the valley at the Highlands (the West Point district). The blockade at the Narrows would be ineffective with the Harlem Valley and Long Island Sound open. With reference to barriers in the course of the great valley, it is to be noted that at any place where a dam can be proposed, in either the Hudson or the Champlain section, the evidence of long-standing water appears quite as high below (south of) the location as above (north of) it. For example, at the Fort Edward divide, the only likely barrier, heavy and conspicuous terraces and unquestioned proofs of standing water lie continuous on both sides of the valley some 300 feet over the col. The idea of drift barriers has no basis in fact or sound theory and may be dismissed.

A rock dam or land barrier to hold the Hudson waters to the high level can not be postulated except by lifting the offshore sea-bottom or continental shelf, as Upham did long ago (8, page 486). We find that the water plane projected south does not drop to sealevel until south of New York City. The gratuitous land barrier would have to lie far out to sea and reach around to New England, so as to block off Long Island Sound. This conception has no basis in evidence and may also be dismissed. There is no scientific explanation of the high level waters in the Hudson Valley except as confluent with the open sea. And every fact and argument also applies to the Connecticut and other low valleys of New England.

The deep submergence of the Hudson Valley since the ice removal is a fact of geologic record, and it must be granted that neighboring territory on the east was involved. But the proof of Long Island submergence is not by any means limited to this indirect evidence. An abundance of direct proof is found in the features of the island, which will be described in later chapters.

EVIDENCE FROM THE CONNECTICUT VALLEY

In a former paper (28) the old problem of the Connecticut Valley terraces was presented and the argument and evidence for submergence briefly stated. Since that publication the study of the marine plane has been prosecuted, and some evidences in the extreme north end of the ancient Connecticut Valley are published in a Vermont report (30).

The proofs of deep and long-lived waters in the Connecticut Valley are the same as in the Hudson and equally convincing. But as the valley is wider the shore features are more detached; the evidences of submergence are not so conspicuous at the summit level and not so readily appreciated as effects of standing water.

It does not seem necessary to repeat here the facts and reason given in the published papers. The summit plain of the uplifted shore features in the Connecticut Valley when projected southward passes high over the sound and Long Island, as shown in the map of isobases (plate 10). As far south as Middletown, Connecticut, the pair of heavy gravel bars at Portland are 220 feet above tide, the figure being the theoretic altitude.

SHORELINES OF THE INNER EDGE

The evident shore-cliff on the face of the moraine on Staten Island and on the west end of Long Island as far as Lake Surprise, six miles beyond Jamaica, has long been recognized as a possible beach. Fuller saw the importance of this scarp as an erosion feature and very clearly describes it under the title, "The great inland cliff of western Long Island." Concerning its origin he says (page 54):

> "That the original scarp was cut in deposits antedating the later Wisconsin drift (probably in the Manhasset formation), that it is the result of erosion, that it was subsequently buried by a mantle of late Wisconsin till, and that it has suffered little subsequent erosion seems clear. . . . The range in elevation of the base of the scarp from 240 feet near Lake Success to 60 feet near East New York, which has always been a stumbling block in the way of accepting the theory of its recent marine origin, is due to the natural slope of the outwash plains built against it, the line of contact with these plains being in no sense a warped shoreline.
>
> "The origin of this scarp appears to be clearly indicated by its topography, every feature of which is duplicated elsewhere on the island under conditions apparently admitting of the absolute determination of its origin. . . . There is little reason to doubt that the inland scarp under discussion is, in its main features, of marine origin, but has been modified by late drift."

Fuller gives other facts and clearly proves the origin of the cliff. If it was not wholly cut in Post-Wisconsin time it is sufficient for the present purpose if it was then standing at sealevel. The slope of the base of the scarp is partly due to land warping, as shown by the map, and partly, as Fuller says, to outwash filling.

Clean-cut, definite shores along the inner margin of the sand-plain farther east are even more significant and quite as conspicuous on the ground, though less evident on the maps. One of the places in the western part of the island is at Farmingdale. Here the plain abuts abruptly against an advanced outlier of the earlier moraine. Five miles eastward, north of Wyandanch, is a similar contact. Similar shorelines may be noted, with more or less clearness, at many points where the moraines stood in water and were exposed to wave-work. Where the moraines were faced by heavy outwash deposits the beach phenomena are less evident. Good localities are northwest of Eastport, north of East Quogue, and particularly northwest of Bridgehampton. These localities are all on the south face of the earlier (southern) moraine. The writer has not examined the northern moraine, but the topographic maps suggest many places where the shoreline may be seen distinctly. In the eastern half of the island the moraines were laid down largely beneath the sea, and the marine shore is usually distinct against the rough, forest-covered hills which stood above the waters and exposed to the waves.

The uniform, smooth, horizontal contact of the sand-plain against the steep, rough faces of the moraines can not be explained except as the work of waves. It is as good evidence of a shoreline as are bars or cliffs.

An important fact in this connection is that these shores, from Staten Island to Bridgehampton, rise steadily eastward at about 1.25 feet per mile, and that they agree very closely with the theoretic marine plane indicated in the map. It should be emphasized that the isobasal lines were projected across Long Island without any reference to its geology and before any study was made of the submergence phenomena.

SMOOTHNESS OF THE PLAIN

The very smooth and even surface of the whole southern plain and the extreme flatness of large areas, specially the south and east portions, would seem to be very strong suggestion, if not actual proof, of subaqueous origin; but the two more recent and exhaustive papers refer the plain, with scant discussion, to subaerial outwash. The work of Veatch and others (25) dismisses the subject of the genesis of the plain with a single sentence (page 45), and says that after the removal of the latest ice-sheet the land stood somewhat above its present level (page 48). Fuller (27) also assumes subaerial origin, and endeavors to explain how the "outwash fans" could unite to produce the flat plains (pages 36-37).

Quoting again from Watson (2, page 443):

> "The surface of this immense plain (Farmingdale to Riverhead) is so nearly level, with only trifling undulations, that the eye can detect no declension. From the ridge to the ocean there is a gradual but imperceptible descent."

The south border of the plain, within a few miles of tide water, carries numerous living streams in poorly defined valleys, the lower stretches apparently drowned as if by recent sinking in small amount. The soils of this belt are more clayey than the ground farther north and more subject to present erosion.

The inner (northern) border of the subaqueous plain, next to the subaerial outwash, is remarkably smooth and flat. Here the channels of the outwash mostly disappear, and the depressions or hollows which do occur are usually without definite limits and lack the characters of stream channels. The surfaces are as flat and smooth as could be expected on a sandy tract steadily lifted out of shallow waters.

In the eastern part of the island some extensive areas, like that between Riverhead and Mattituck, are perfectly level, unbroken plains except for the kettle basins. These basin features will be considered later.

SURFICIAL LOAMS

Some facts connected with the surface soils and composition of the plain are inconsistent with the theory of subaerial origin. The occurrence of loamy surface soils over considerable areas, giving good farm lands for general agriculture, was long ago recognized. Watson wrote (2):

> "There prevails the same superficial loam, from one to three feet deep; then succeeds small gravel mingled with the loam, which rests on the uniform foundation of coarse and rounded gravel" (page 494).

If the plain had been wholly built by glacial outwash in the open air, the finer detritus would have remained in the grasp of the storm wash and streams until dropped in relatively quiet standing water. The fact that such fine material now forms a veneer over large areas proves that these areas were under water. Erosion in the shallow water and in the air has removed the veneer of silts along the lines of flow, so that the depressions and channels show sand and gravel. Watson wrote:

> ". . . and it is a singular circumstance, which marks the anomalous arrangement of the whole island, that unlike every other territory the soil is thinnest and least fertile in depressions than on the elevated parts of the surface" (page 487).
>
> "The greatest thinness and barrenness of soil occurs in the depressions, while the best and heaviest land is found on the elevated parts of the plain. . . . Ravines running north and south traverse, at intervals, the plains, and these, uniformly, have the lightest and thinnest soil" (page 495).

It is possible that Watson confused in some cases the exposures of stiff brick clay of preglacial or interglacial origin which underlies the glacial outwash and in the moraines is pushed up in masses and involved with the till; but, making allowance for this and for his rather sweeping statements, it is yet true that he properly emphasized the loamy character of much of the plain.

Another interesting fact is the absence of stones over most of the southern plain. On large areas scarcely a pebble can be found.

The absence of boulders on the plain, while abundant along the moraine, was by Lewis attributed to disintegration. But postglacial weathering has not been more effective on the plain than on the moraine. With the subaerial theory we should expect coarse material and even boulders along the stream channels. Under submergence we might expect them to be rafted out on the plain by floating ice. The probable explanation is that the waves prevented ice-blocks from voyaging far from shore, while the underflow by stream or tide was not competent to move large stones far from the beach. We do find cases of ice-rafting in the secluded waters, which will be described later.

SUBMERGED MORAINES

No writer appears to have recognized the striking difference in the surface expression of the moraines. Montauk has good moraine relief, being part of the outer moraine belt; but the hills are rounded, softened, subdued, and very unlike the moraine at Bridgehampton or the hills along the north side and west end of the island. This subdued character pertains also to the Shinnecock Hills. It is found that these subdued moraines have been cleared of forests, while the rough moraines are left in timber. The explanation of this difference in the moraine surface is found in the fact that the cleared hills with softened outlines were beneath the marine waters. This is indicated in the map. The theoretic marine plane clearly separates the smoothed, lower moraines from the higher and rough, unsubdued moraines.

The sandy or somewhat duny surface of the Shinnecock Hills, noted by the early writers, was doubtless an effect of their submergence. It is possible that part of the sand might have been derived from Shinnecock Bay, but if so the work should be in progress today. The Montauk Hills will probably show some stratified sands in the hollows. Fuller says:

> ". . ., a mantle of dune sand materially altering the surface relief of the Shinnecock, if not of the Montauk Hills. The former were covered with drifting sand hills when visited by Timothy Dwight as late as 1822" (page 35).

Fuller selects as special examples of the very diversified morainal topography the high, detached and unsubdued hills east of Manorville, north of East Quogue, and between Hampton Park and Sag Harbor (page 33). These are the only portions of the earlier moraine in the east end of the island which stood above the sea. Just between the East Quogue and the Hampton Park Hills lies the Shinnecock group, a well developed part of the same outer moraine, but with strikingly different expression. If all the island and the moraines stood above the sea, then why this difference? A similar difference is found in the eastern remnants of the later moraine, the limitation being the marine plane shown in the map. Fuller seems to have had some doubt as to the nature of these wave-washed moraines. He called them, with some misgiving, "depressed moraines" and defined them as follows:

> "In brief, the term is applied to irregular marginal accumulations developed along the ice-front in line with the normal morainal ridges, but failing to rise above the adjacent outwash. The 'depression' is due rather to the non-accumulation of morainal material than to an excess of outwash" (pages 33-34).

The Shinnecock and Montauk masses have no deficiency of material. They simply have lower altitude, and partial submergence of the moraines is the perfect explanation.

East of the meridian of Manorville the later moraine was mostly submerged or has been cut away by wave erosion. The submerged, sandy moraines Fuller calls "pseudomoraines" (page 35). He says that they are largely dune sand, although having morainal topography. The characters and genesis are probably similar to those of the Shinnecock Hills.

KETTLE PLAINS

Another peculiar feature, closely related to the subdued moraines and equal proof of the submergence of the island, is the occurrence of many kettles far out on the plain beyond the moraines. The kettles of the island have been admirably described by Fuller (27, pages 38-44), but the significance of those in the plains has not been recognized.

Kettles occur profusely in the moraines, which is where they specially belong, and may occur wherever the stagnant ice-margin has lingered. No kettles occur on Long Island in the outwash plain and none in the submerged plain facing the sea until we pass east to Shinnecock. A single exception is the small basin northwest of Babylon, of uncertain origin.

Kettle plains are found at Southampton and Bridgehampton and eastward, in connection with or facing the earlier moraine, and through the low area between the two moraines east of Yaphank and Rocky Point. Riverhead and Mattituck lie in a district rich in kettles. Some portions of the kettled areas are as flat and smooth as any parts of the island. The village of Bridgehampton is surrounded by kettles, which occur within one and one-fourth miles of the ocean beach and three miles beyond the rough moraine. And this is a level district, with much loamy surface soil.

The southern limit of the kettles is shown on the map by the line that touches the south edge of the Shinnecock Hills and the sharp moraine north of East Quogue.

What is the explanation of these kettle plains? Ice-blocks of size sufficient to produce the kettles could not be transported by subaerial glacial outwash. If rafted out into standing water they could not sink and be buried. The kettles must represent drift-anchored ice-blocks which mark advanced positions of the ice-margin. The ice-blocks were buried in drift which was leveled before the blocks melted.

The kettles certainly represent morainic conditions. If the moraine was built in the air, as required under the theory of elevation for the island, then why do the kettle areas not have morainal topography? Either the moraines of the kettle areas were deposited under water or the land was carried down and wave-leveled and then lifted out again before the ice-blocks melted. A brief discussion of the mechanics of kettle formation has been given in paper number 28, pages 232-233, in which it was argued that larger ice-blocks deeply buried probably would not melt until the locality was exposed to the atmosphere.

It should be noted that all the areas of kettle plains, like the smoothed moraines, lie beneath the theoretic plane of marine submergence.

STRATIFIED SANDS CONTAINING BOULDERS

An interesting feature and another proof of submergence is the occurrence within the moraines of fine, stratified sand with included boulders. The writer has observed this only in the heart of the moraine northwest of Bridgehampton, but similar phenomena are likely to occur in other places. About two miles northwest of Bridgehampton, and about one-half mile beyond the house of Mr. William D. Halsey, is a basin or kettle in the low valley which intersects the moraine. At altitude of about 140 or 145 feet, by the roadside, is fine sand with included ice-rafted boulders. The locality is 15 or 20 feet beneath the marine plane. The deposit can not be attributed to glacial waters or pools within the moraine because the valley opens freely southward. The fineness of the sand rules out the idea of stream-work or outwash, and the inclusion of boulders indicates some depth of water for the floating ice. The marine plane has here about 160 feet altitude, and two valleys which traverse the moraine were swept by the sea.

Such phenomena should be expected in the secluded, sheltered valleys of the moraines. Under the conception of subaerial deposition of the sands they would probably be attributed to glacial waters.

EQUIVOCAL FEATURES

ABSENCE OF BEACHES

The one negative point, and the only one effectively used against the suggestion of marine origin of the sand-plain and of other similar plains in New England, is the absence of unequivocal, distinct beach phenomena on the plains. The necessity for beaches has been tacitly assumed. It will be shown that this assumption is wrong.

Dr. F. J. H. Merrill[2] is the only student of the subject who has discussed this point. He showed a clear appreciation of the problem and gave good explanation of the absence of beaches. The following quotations are from Merrill's paper (11, pages 105-109):

> "On Staten Island and western Long Island alluvial plains of stratified material rise gently from the ocean shore to the margin of the moraine, terminating at an altitude of about 80 feet, and although no continuous shoreline is to be found, the plains are referred provisionally to the same period as the estuary deposits a few miles north.
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> "The records of ocean wave action are in many cases different from those of the extinct quaternary lakes and not so easy to recognize. It is not always possible to decide a question of submergence by the presence or absence of a distinct shoreline. On a lake shore wave action tends to cut in an horizontal plane, and the result is a series of terraces or a beach plane associated with shore drift and littoral deposits in various phases. When ocean waves act on a shoreline there may be two cases:
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> "1. The land may be at rest. In this case the result will be the same as on the shore of a lake which maintains its level for a comparatively long time.
>
> "2. The land may be rising or subsiding with respect to sealevel. In this case the plane of erosion will be a resultant of two planar forces: A, the wave force which operates in an horizontal plane; B, the force of elevation or depression which acts in a vertical plane." . . .

After discussion of the effects of the interaction of the two forces, he concludes his analysis of the mechanics of beach cutting as follows:

> ". . . for the present purpose, which is simply to point out the fact that a land surface in process of subsidence or emergence may be subjected to wave action without being incised with distinct shorelines, and also that *wave action may produce an inclined plane as well as a terrace or baselevel.*
>
> "It is therefore evident that submergence would not leave a deeply cut shoreline as its record unless the rates of land movement were so adjusted as to permit of it. In fact, no very distinctly cut shorelines are to be found on the drift about New York, even at an altitude corresponding with that of the Hudson estuary deposits. Apart from the still-water deposits the 80-foot postglacial depression about New York can only be traced by change of surface

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[2] While this article is in preparation Doctor Merrill has passed away. The writer regrets that he has not lived to see the verification of his theory.

> slope and material at this level. Even these two varieties of evidence are not always coexistent." . . .
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> "As the land rose from its 80-foot depression at New York there seems to have been a brief period of less rapid elevation, during which a second series of estuary terraces and alluvial plains were formed which now stand about 25 feet above tide level. These have been recognized on Staten Island by Dr. N. L. Britton and may be seen on the Harlem River near Fordham Heights and at various points on the Long Island shore of Westchester County."

Prof. N. S. Shaler recognized the marine origin of the low sand-plains of Marthas Vineyard and Nantucket and noted the absence of beaches. His explanation was the too rapid rise of the land, stated as follows:

> "The emergence of the drift deposits of this district from the sea must have taken place with singular rapidity, for there are no signs of wear on the surface of the moraines or the low-lying kames, such as would inevitably have occurred if their surfaces had been exposed to the action of the waves for any length of time."[8]

The writer is able to confirm Merrill's views and to prove, from field study, the absence of beach phenomena on sand stretches of strong shorelines.

Probably most students of shorelines have found gaps along otherwise strong beaches. It requires a long time at a fixed level for waves and shore currents to bridge unfavorable stretches. On shores as strong as that of the glacial Lake Warren and Lake Iroquois localities are found with only smooth, wave-washed slopes, comparable to the inner edge of the Long Island plain. With changing levels the construction of beach phenomena—bars, spits, and cliffs—is more difficult. In postglacial time the land was rising (rapidly or slowly, according to the mental viewpoint) and the beach-building work was constantly shifted to lower and lower levels. The conditions of changing attitude immediately following the removal of the ice-sheet were unfavorable for beach-building.

On the open seashores of Staten and Long islands another inhibiting factor existed which was not present with the glacial lakes, namely, the tidal fluctuations of level. A slight change in the water level may produce large variation in the force and direction of shore currents and effectively change the plane of beach construction.

There is yet another factor in this connection which seems to have been overlooked, but which is of equal or perhaps of more importance than those just mentioned. It may be illustrated by examples from the field. On the north boundary of New York is the projection of high ground from the Adirondack mass locally known as Covey Hill. Around this salient lie the beaches of the ocean-level waters—the Champlain Sea—some stretches in splendid form, but in some places weak. The summit level is about 740 feet. At a lower level, about 525 feet, is a declining series of heavy cobble bars passing near Covey Hill post-office, Maritana and Franklin Center, before it passes southwest into New York north of Chateaugay. When we follow the summit series of cobble bars southward from Covey Hill along the Champlain side of the highland, we find it increasing in strength and remarkably well developed as far south as the parallel of Port Kent or to the south edge of the Dannemora quadrangles. But the Covey Hill Post-office series of bars, which are the stronger bars on the north end of the salient, weaken southward and disappear near West Plattsburg, in the northeast corner of the Dannemora quadrangle, and have no strength anywhere to the south. Two miles northeast of West Plattsburg this shoreline is only a rolling plain of sand, like other vast areas in the submerged Champlain Valley. This locality had as good exposure as where strong beaches occur. The waters stood there just as long, and fine beaches are found occasionally at lower altitudes. What is the explanation? Only the difference in the material. The bars and spits are cobble or gravel. Where the waters found only sand they were unable to build embankments. On the Vermont side of the broad Champlain Valley, with good exposure to the stronger winds, the shore embankments are in coarse materials. Some small bars of sand are found on lee slopes or in sheltered places where weak waves found a small amount of material proportionate to their power. A good example occurs on the east slope of the Williston Hill, in Vermont (30, page 25). All the heavy beaches in the sealevel waters in the Hudson, Champlain, and Saint Lawrence valleys are coarse materials, never sand. Even the steadier level of Lake Iroquois produced only cobble bars in the stretch of short-lived waters between Watertown and Covey Pass. On the extensive delta plains, with superabundance of sand and fine gravel, beach features are practically wanting. An abundance of sand seems to have inhibited bar construction, even when there was considerable coarse material. Long Island must have been lifted through the sealevel waters as rapidly as was the Champlain region and the physical conditions were similar. But Long Island and Staten Island (also Marthas Vineyard and Nantucket) were at a disadvantage for production of beach phenomena, as the shores were exposed to tidal changes of level and the glacial outwash was so profuse that the shallowed waters could do no more than distribute it. The condition of shallow and ineffective shore waters with superabundance of fine materials persisted over all the rising plain.

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[8] Geology of Marthas Vineyard. Seventh Ann. Rept., U. S. Geol. Survey, 1888, page 321.

The only conspicuous shoreline is the clifflike front of the moraine on Staten Island and on Long Island as far northeast as the meridian of Manhasset. There now seems little doubt that this is an erosional feature. The conditions favoring erosion appear to have been: (1) Less amount of outwash; (2) steeper original front of the moraine; (3) deeper offshore waters, and (4) perhaps exposure to stronger winds. Over most of the island the offshore waters were shallow and weak and could do no more than distribute the detritus. Near Brooklyn the apparent cliff probably represents the advanced position of the ice-front. While the waves in the Southampton-Bridgehampton district were leveling the deserted moraine the waters in the Brooklyn-Jamaica district were probbaly eroding the bold front of the heavy moraine. From Queens to Lake Surprise the base of the cliff has been buried by the heavy outwash of gravel.

ABSENCE OF MARINE FOSSILS

This has never been seriously urged as an objection to marine origin of the Long Island plains, as it is recognized that great sand terranes are sometimes entirely devoid of organic remains; but it has been used as objection to marine genesis of the Hudson Valley deposits.

The writings of Lewis contain references to marine shells being found on the island; but these occurrences are not described and some of them are much above the marine plain. As shells occur in the pushed-up drift of the moraines, and even masses of beach deposit composed largely of marine mollusks occur associated with Pre-Wisconsin clays in the heart of the moraines, it is probable that all of Lewis' fossils are older than the frontal plain. Watson also speaks of shells, some being found in the "channels." No value is placed on these accounts, and the chances are small of ever finding any fossils in the sand-plain. It is possible that they may be found in some quiet-water deposits in the moraine valleys.

Explanation for the lack of marine fossils in the Hudson Valley has been already published (28, page 242; 30, page 4). All the earlier and higher waters of the Hudson-Champlain inlet and strait were confluent with the sea, but not saline. The Hudson today is sealevel, but brackish only to about the highlands. As long as the glacier front excluded the marine waters of the Saint Lawrence Gulf, all the flood now represented by the Saint Lawrence River, as well as the large volume from the melting ice, was forced south through the narrow passes at Whitehall and at West Point. With this flow of fresh water it would appear quite impossible for saline water and marine fauna to enter the Hudson Valley, and before this flow ceased the lower Hudson Valley was partly, if not fully, raised to its present height. Before salt water was admitted to the Champlain Valley, through the Saint Lawrence Gulf, the divide at Fort Edward perhaps was raised above sealevel. The total uplift there has been about 440 feet, and the col today is 150 feet above tide.

CREASES ON THE PLAIN

All writers on the physical features of the island have noted the peculiar characters of the drainage lines. The variety of names applied, as "dry rivers," "creases," "furrows," etcetera, indicates that they are unusual, indefinite, and puzzling. Such careful workers as Salisbury and Woodworth have referred to them as anomalous in form and doubtful in origin. The earliest writers did not recognize the glacial outwash of the higher parts of the plain, and later writers failed to see the subaqueous origin of the lower plain. We now know that quite all of the east half of the island and the entire extent of the south shore were under the sea while all the subaerial outwash was building. There was dual origin of the sand-plains, with different drainage features. Writers have not discriminated, but have discussed the features as a whole. The channels of the moraine and outwash should be treated distinct from the depressions in the marine plain. The fullest description of the former is by Fuller (27, pages 46-48). No one has specially described these submarine features of Long Island; but Shaler's discussion of similar forms on the marine plains of the islands off the Massachusetts coast may be sufficient:[4]

> "The formation of this inclined plain of sand beneath the level of the sea fully accounts for its general features; for in all respects, except in the presence of the channels before described, it essentially resembles the bottom of the sea as it exists south of this shore. The angle of the slope seaward is the same and, so far as we can judge by the soundings, the character of the materials in the two terraces does not differ in any important respect. The only difference is that on the existing sea-floor there appear to be no such channels as we are endeavoring to explain. We are therefore fairly driven to seek the origin of these channels in some forces which were at work during the glacial period, and there are no others which seem available save the subglacial streams, the existence of which is proven to us in many ways" (page 318).
>
> "These troughs generally terminate in the various ponds or coves which indent the southern shore of the island (Marthas Vineyard). In fact, these inlets are formed in the southerly extremity of the depressions, where they deepen toward the sea and have been widened by its action. . . . These depressions are best studied on the similar southern plain of Nantucket, where the treeless character of the surface clearly reveals their form. The striking

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[4] Report on the geology of Marthas Vineyard. Seventh Ann. Rept., U. S. Geol. Survey, 1888, pages 297-363.

peculiarity of these troughs consists in the fact that though in form much like ordinary stream beds they are not now and never have been the seats of subaerial rivers. Their valleys, often several hundred yards in width, do not present the smooth downward grade so characteristic of ordinary valleys; their floors are generally more irregular than those of any ordinary stream could be. Nor do they have the distinct banks common to all land streams. The only explanation which can be given of these troughs is that they were the channels through which the subglacial streams found their way seaward" . . . (page 317).

"It is not unlikely that when once instituted by the subglacial stream these valleys would have been somewhat further developed by the to-and-fro movement of the tides along shore. The outrunning streams from the glacial face would have tended to determine the outflow of the tide into their channels, thus increasing their scouring action" (page 318).

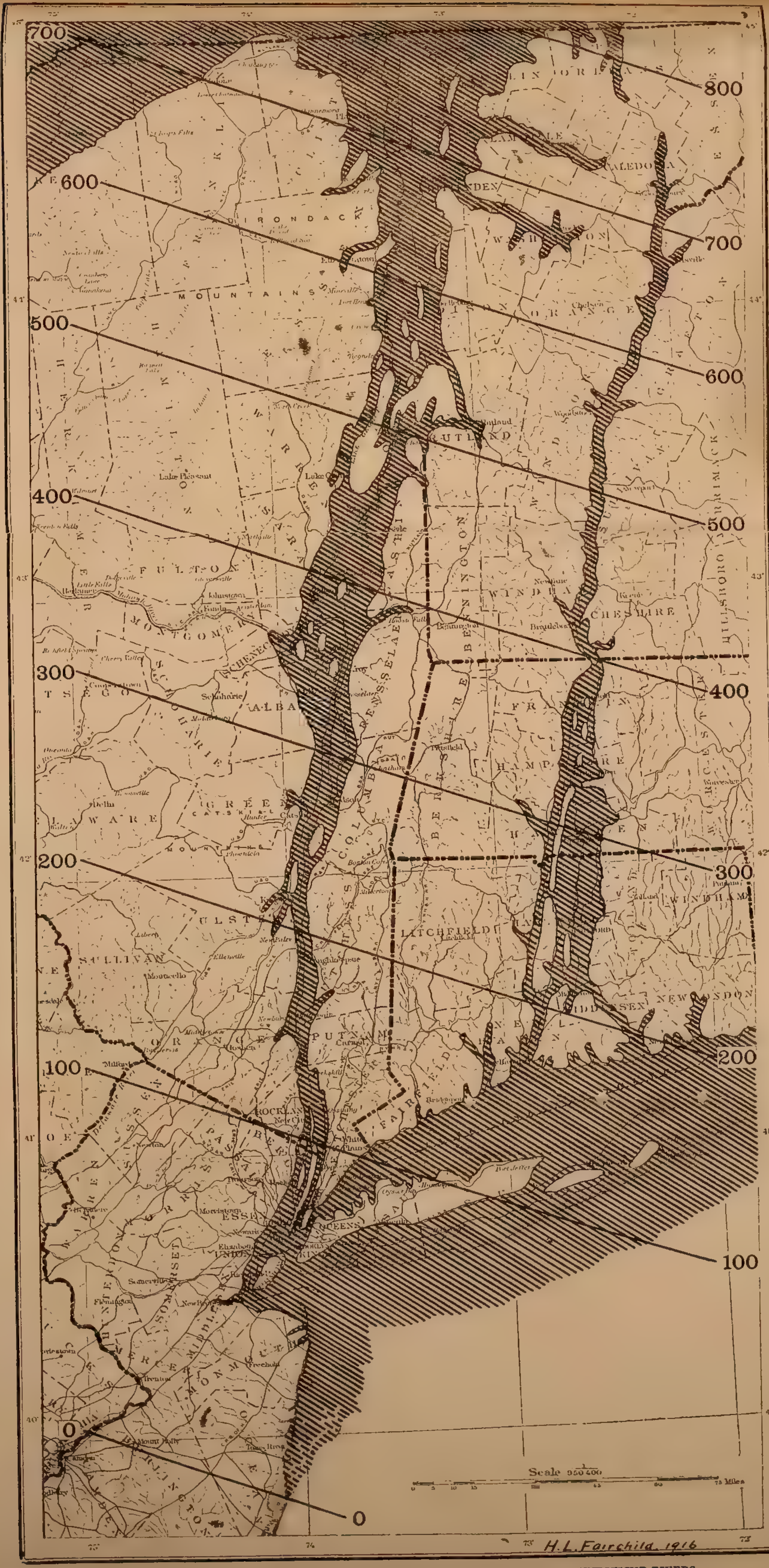
"In studying the form of these old channels, especially on Nantucket, where they are best shown, we observe that they gradually widen as they depart from the front of the moraine until at a distance of from three to six miles from their origin they are from five to twenty times as wide as at their source. We also note that the streams which form these channels apparently diminished their energy of movement in proportion to the distance traveled from the glacier. This is shown by the much finer sediment which they laid down in their outer parts. Near their sources they were able to move considerable pebbles, while at their southern extremities they were able to transport fine sand alone.

"I desire to say that while these peculiar channels may not in the end appear to be due to the causes above suggested, this cause is the only one out of many considered which appears reconcilable with the facts. They are clearly due to localized streams of some sort which originated at the ice-front. They were evidently formed while the surface on which they lie was depressed below the level of the sea, for their troughs do not have the shape of those excavated by subaerial streams" (page 319).

If we are unable to fully explain all the peculiarities of the plain, it is because we are ignorant of the precise mechanical conditions and operations involved in the lifting of a gently sloping sand-plain out of tidal waters. It would be unwise and unfair to let such uncertainty outweigh the abundant, clear cut, positive proof of submergence.

Explanation of Maps and Isobases

In plate 11 the shaded areas indicate approximately the greatest submergence of the land and the broadest extent of the sealevel waters for all localities, but not all at the same time. The northward-moving wave of land uplift, following the receding glacier, was lifting the land on the south and thereby diminishing the waters, while the land on the north was at its lowest attitude. Perhaps Long Island had attained nearly its present height before the Champlain district began to rise.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CHESHIRE
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SUBMERGENCE AND UPLIFT IN THE AREAS ADJACENT TO THE HUDSON AND CONNECTICUT RIVERS

The shaded areas show the maximum of submergence; the isobases indicate the amount of post-Glacial uplift

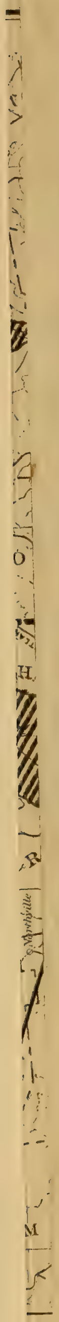
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Plate 11 is slightly modified from the one published in this Bulletin, volume 25, plate 11. These maps are the result of field-work extending over several years and examination of both sides of the Hudson-Champlain Valley from New York City to Canada. The detailed description of the shoreline in New York is awaiting publication by the New York State Museum, but the Vermont shore is described in the Report of the Vermont State Geologist, 30 of the list of writings, page 308.

The lines of equal uplift (isobases) drawn on the accompanying map were originally projected across Long Island in accordance with the data of submergence of the Hudson and Connecticut valleys, and were found to be in close accordance with the facts as observed on the ground. The difference favors slightly greater submergence than the projected isobases indicated, and the lines are here drawn in accordance with the field study.

It is recognized that the isobases must eventually curve northward to lie somewhat parallel with the eastward margin of the glaciated and depressed area. The direction of the lines as plotted carries them far out to sea (see also plate 12, in volume 27, of the Bulletin), and suggests a deeper submergence of New England than has usually been recognized. But it should be noted that Shaler thought there had been submergence of Marthas Vineyard to a depth of 300 feet, which is more than the isobases indicate.[5]

Thus far in this writing no movement of the island has been suggested except the postglacial uplift to the present altitude. It is possible that the rise in recovery from depression carried the land up higher than it now stands. This might explain some features on which Veatch, Fuller, and Crosby postulated the higher attitude of the island at the close of Wisconsin time.

There are other possible factors affecting the water level which are not here taken into account. One is the gravitational pull of the ice-sheet on the marginal waters. Another is the rise of ocean level due to the return of the ice-caps to the sea. The effect of the latter factor is to reduce the apparent submergence. The diastrophic and marine-level problem is complicated by these indeterminate factors. The present land attitude may be only the final averaged result or sum of all positive and negative elements. But the maximum difference of postglacial land level could not be less than now exists, as shown by the isobases; it might have been more.

The former shorelines of the time of land depression are mostly approximate on the map and very generalized. As beaches are absent on the smooth sand-plain, for reasons already given, the broken boundary line between the subaerial outwash and the suboceanic plain is located somewhat arbitrarily in accord with the theoretic altitude of the marine plain. But where the sand-plain abuts against the rough moraines, with no intervening outwash, the shore is clear and surprisingly accords with the theoretic level. These shores are indicated by solid lines, as seen at Farmingdale and north of Bridgehampton. Future study will probably find a general accordance everywhere.

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[5] Loc. cit., page 320.

The southward limit of the kettle areas is shown by a hachured line. The ice-front certainly reached to this line and perhaps farther.

SUMMARY

The partial submergence of Long Island under the weight of the ice-sheet was predicated from the position of the isobases connecting points of equal submergence in New York and Connecticut. Examination of the surficial features of the island confirms the prediction.

The earlier writers recognized the marine origin of the plain, and Messrs. Darton, Davis, Merrill, Ries, and Salisbury published superabundant evidence of deep submergence of the New York City district and the Hudson Valley.

It is found that direct proofs on the island of submergence equal in amount to that indicated by the isobasal lines are abundant and even conspicuous. These are: (1) Conspicuous shores where the sand-plain abuts against the high and rough moraines; (2) the smooth surfaces of the plain; (3) the composition of the lower plain and its loamy superficial soil; (4) the subdued character of the moraines which lie beneath the theoretic plain; (5) wave-leveled morainic tracts, indicated by the many and large kettles; (6) stratified sands in open valleys, with included boulders; (7) terraces and delta plains north of the moraines at the theoretic height; (8) the submergence of neighboring territory, the Hudson and Connecticut valleys, and (9) the accumulating evidence that the Labradorian ice-body weighted down all its buried territory, and that Long Island was well within that area.

The greater plain of the west half of the island is found to have dual character, some limited and higher portions being subaerial glacial outwash, with no clear line of demarkation from the subaqueous plain.

The altitudes of the shorelines and the uniform slant of the water-produced features is in good agreement with the theoretic marine plain. This rises from about 60 feet at Brooklyn to about 160 feet on the moraine north of Bridgehampton.

The lack of beaches (bars, spits, etcetera) is shown, by many examples of such deficiency on strong shorelines, to have no negative value. The inhibiting effect of large volume of sand, the rising of the land, and the tidal variation of water level all conspired to prevent the construction of embankments. The absence of fossils in the sand-plain is to be expected, while the absence in the Hudson deposits was due to the enormous flood of fresh water forced southward through the valley during all the time of deep submergence.

The form and general characters of the depressions and creases over the plain are admittedly not normal drainage features, but are such as would occur on a sand and clayey plain of gentle slope rising out of tidal waters.

The combination of surficial features of the Long Island plain could not possibly be the product of any subaerial processes, but are precisely the effects of standing water. No facts have been found in contradiction of marine submergence.

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VOL. 28, PP. 309-322, PLS. 12-17 JUNE 9, 1917

PLEISTOCENE AND POST-PLEISTOCENE GEOLOGY OF WATERVILLE, MAINE[1]

BY HOMER P. LITTLE

(*Read before the Society December 29, 1916*)

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INTRODUCTION AND ACKNOWLEDGMENTS

The material of this paper was prepared with two objects in view: first, to describe and interpret some of the sections exposed in the vicinity of Waterville, and thus add to the small amount of detailed literature existing on the Pleistocene of Maine; second, to add to the list of Pleistocene fossils of Maine, as published by various workers and tabulated by Clapp,[2] a few forms collected here during the past five years. The facts presented were collected in connection with work with my classes at Colby College, supplemented by some work during the summer. The identifications have been made through the kindness of Prof. E. W. Berry, of Johns Hopkins, to whose encouragement, indeed, is due the preparation of this paper.[3]

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[1] Manuscript received by the Secretary of the Society January 4, 1917.

[2] Bull. Geol. Soc. Am., vol. 18, 1908, pp. 520-523.

[3] Thanks are also due Professor Carter, of our department of surveying, to whose kindly interest was due the accurate determination, with the Y level, of the elevations at which the fossils of the area occur.

DESCRIPTION OF THE DEPOSITS

DISTRIBUTION

Waterville is located on the Kennebec River, 18 miles above Augusta, the capital of the State, and 81 miles above Portland. The distribution of the deposits here is as follows: Above a level of about 160 feet the bedrock, where exposed, is covered with a deposit of ground moraine. I have not been able to discover any special sequence of events in these deposits. Below this level, in the valleys, a definite sequence is often evident. This consists of an older series of sands and gravels, an older series of sands and clays, an apparently younger series of gravels, and a younger series of sands and clays. Of these, the older sands and clays are clearly estuarine, while the younger ones are probably fluviatile; the older sands and gravels are glacio-fluviatile, while the younger ones are of uncertain origin.

THE OLDER SANDS AND GRAVELS

The main exposure of these sands and gravels in this region is in the form of an esker, extending from north of Fairfield through Waterville, a distance of several miles. Figure 1, locality Y, shows it where best developed. At first it is a very well defined, continuous esker, but as Waterville is approached it becomes much broken. In this esker are found many gravel pits, and the only satisfactory exposures are in these. The base of the deposits is nowhere to be seen, but since exposures of striated slate are found near by and at about the height of the esker, it seems likely that they rest on ledge. They may, of course, rest on drift which the esker stream failed to remove, but evidence of this is lacking; in none of the pits have I found stratified deposits resting on unstratified.

The more or less definite variation in these deposits may be seen in plate 12, figure 1. At the base here, though not showing in the photograph and usually not exposed, are very uniformly grained, decidedly cross-bedded sands. These are buff in color, mostly quartz, and rather sharp, though fine. The true bedding is horizontal. There is a sharp line of differentiation between them and the overlying deposits. This overlying deposit is composed of small gravel or coarse sand and is very clean, resembling the deposits underlying the "gravel rips" of many streams. The color is smoke. The gravel consists very largely of flat fragments of shale, the two longer axes parallel to the stratification. This may be good to poor, depending on the locality of the section. At times it is very evident, as in plate 12, figure 2. Here the gravel is overlain directly by sands of the marine series, but usually there is a deposit of

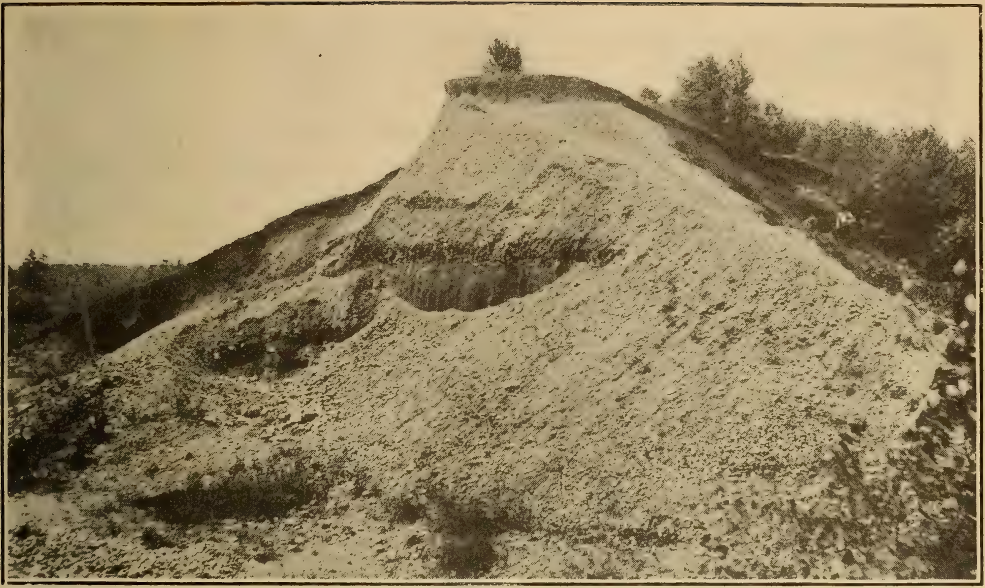

FIGURE 1.—SECTION ONE-HALF MILE WEST OF FAIRFIELD, MAINE, LOCALITY Y

This shows the fine smoke-colored gravel, the coarse "light" gravel, and the steeply dipping contact with the sands at the base of the marine clay formation

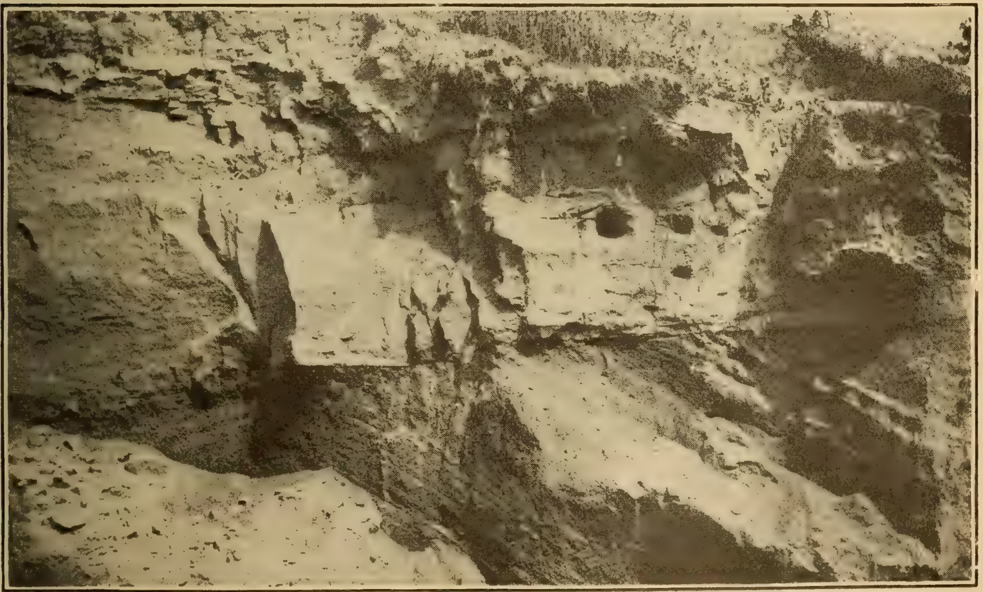

FIGURE 2.—SECTION DIRECTLY ACROSS THE ROAD FROM THE ABOVE

This shows that the sloping contact of the sandy layer of figure 1 brings it into contact with the smoky gravel, as seemed likely. The stratification of the smoky gravels is here very distinct. Some of the finer layers are decidedly cross-bedded. The gradation of sand into clay can be seen in the upper left-hand corner.

RELATION OF GLACIO-FLUVIATILE AND MARINE FORMATION, FAIRFIELD, MAINE

coarser gravel intervening, as in plate 12, figure 1, and plate 13, figure 1. This coarser gravel is the top member of the lower sand-gravel formation. The contact as seen here is very sharp; the cobbles of the lower two feet are embedded in fine sand, or else porous and covered with a film of clay. In most sections the contact is not so sharp as here, although as a rule there is clearly a lower finer member and an upper coarser member. This gravel gives the impression of being light brown in color. The gravel dealers generally speak of it as light gravel, as opposed to the lower deposit, which they call dark. The gravel is rounded to subangular and shows no striations, so far as observed. Stratification is not distinct except when viewed in sections transverse to the esker, when it is fairly evident.

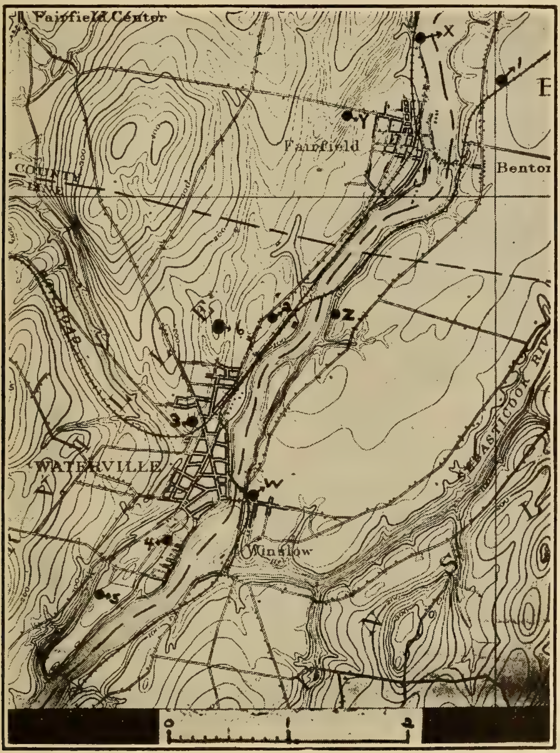

FIGURE 1.—*Topographic Map of the Area under Discussion*

Letters indicate localities where the more important photographs were taken; numbers indicate localities where fossils were found, as well as photographs taken

The chief feature which needs to be explained in regard to the lower sands and gravels is the change in coarseness from top to bottom, the suddenness of the change, and the rather homogeneous character of the material bounded by each change. Two explanations at once suggest themselves: first, that the varying deposits represent variations in stream velocity, due to weather changes; and, second, that the variation is due to a sudden accession of water gained through piracy of other water-courses within the ice or the formation of new fissures admitting an increased supply from the surface. The most likely supposition for the two upper members seems to me to be the simple one of variation in weather. This is borne out by the fact that in many exposures similar beds of finer and coarser gravel alternate, as seen in plate 13, figure 2. New accessions of water by the methods pointed out must also surely have played some part in the variations.

The lowest of the three members composing the lower gravels, and described as a fine, buff, quartzose sand, is not so easily explained. Its relations are not clearly exposed at any point, but at the best exposure it extends out several yards along the flat to the east of the esker, and also underlies the other deposits of the esker at about the same level. If it were not for the fact that it underlies the other deposits of the esker, it would be natural to look on the sand as a delta deposit in connection with the retreating glacier, or as a lateral deposit in a widened esker channel; but if that were true, it should grade into the coarser deposits rather than underlie them, with no apparent change of character. It certainly is not a glacial deposit, for it is perfectly sorted and beautifully cross-bedded. Its interpretation is made more difficult by the fact that there is nowhere an exposure showing on what kind of material it rests. Its position is just that which a preglacial deposit would occupy, such as might be formed in front of the advancing ice-sheet by small streams in a short melting season; but the difficulties in such an explanation—such as the preservation of so loose a deposit—are so great that I would not care to advance this as a probable explanation.

THE OLDER SANDS AND CLAYS

Overlying the lower sands and gravels is the marine clay formation, often divided into a lower member, the Leda clay, and an upper member, the Saxicava sands. It overlies unconformably the coarse or fine gravels or rests directly on the slate. This unconformity has been considered by some to represent merely the preexistent irregular surface due to drift and fluvio-glacial deposits. There is no question but that the base of the clay would be exceedingly irregular, even though the surface on which it rests had never been subjected to erosion. Nevertheless most of the sections seem to show evidence of further increase of irregularity through

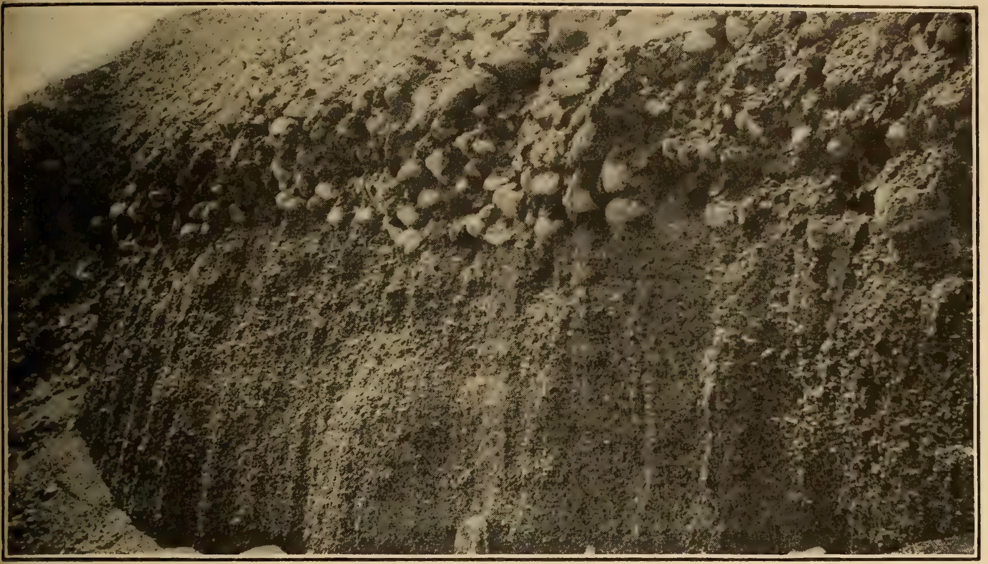

FIGURE 1.—DETAIL FROM FIGURE 1, PLATE 12

Shows the very sharp contact between the smoky and coarse gravel. The apparent lack of stratification, when viewed longitudinally to the esker, as here, is in striking contrast to the distinctness of stratification in cross-section, as in figure 2, plate 12.

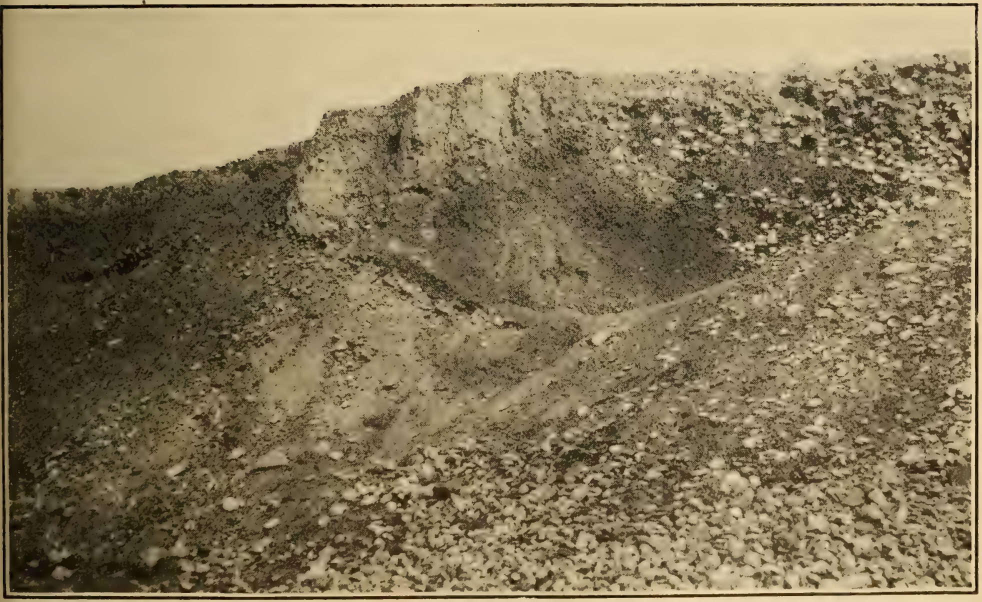

FIGURE 2.—CONTACT OF GRAVEL AND FOSSILIFEROUS CLAY, LOCKWOOD GRAVEL PIT, WATERVILLE, MAINE, LOCALITY 5

There is a well defined layer of fine gravel between two coarser ones. Note the basal conglomerate at the base of the clay, especially prominent where it crosses the fine gravel. The clay is abundantly fossiliferous just to the left of the kodak case, barnacles being especially abundant even into the basal conglomerate.

SECTIONS OF GRAVEL AND MARINE CLAY, WATERVILLE, MAINE, AND VICINITY

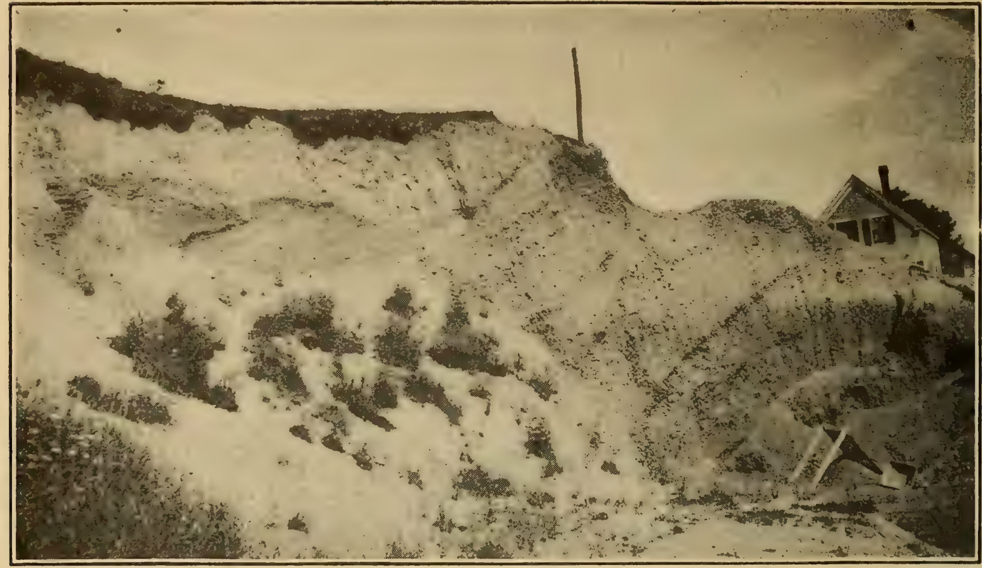

FIGURE 1.—SECTION IN SMALL GRAVEL PIT, WATERVILLE, MAINE, NEAR LOCALITY 3

Shows the apparent subaerial nature of the erosion at the contact of glacio-fluviatile gravels and marine sand and clay. The undulatory nature of the contact is thought to indicate a brief interval of erosion before the submergence.

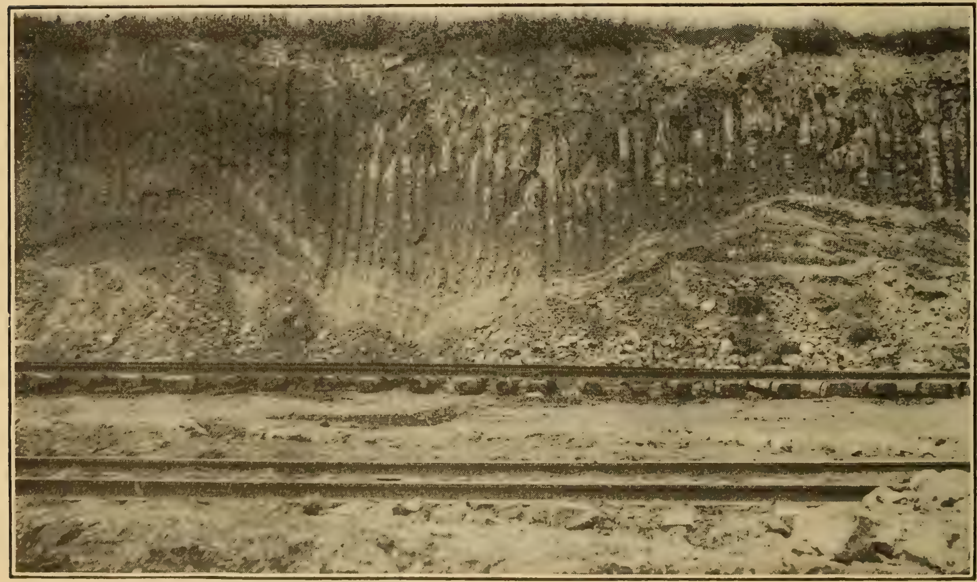

FIGURE 2.—SECTION WHERE ESKER CROSSES KENNEBEC RIVER, ONE MILE NORTH OF FAIRFIELD, LOCALITY X

Shows unconformity at contact of esker gravels and marine sand and clay

RELATIONS OF GLACIO-FLUVIATILE GRAVELS AND MARINE CLAYS, WATERVILLE, MAINE, AND VICINITY subaerial erosion. This shows especially well in plate 14, figures 1 and 2. It has been suggested that the gravels were formed beneath sealevel and the clay deposited directly on the uneven surface as soon as the inclosing ice melted. Katz and Keith have recently strongly advocated such a relation between the moraine and "Leda" clay along the coast of Maine.[4] Such does not seem to have been the case in the region about Waterville for the following reasons:

1. If the esker were submarine, it does not seem probable that a basal conglomerate, such as is so clearly shown in plate 13, figure 2, locality 5, would have formed. As Katz and Keith pointed out,[5] the uniform character of the clay requires fairly deep water as the condition of origin. It does not seem likely that such a deep water condition of origin, supposed to have been realized at once on the melting of the ice, would favor the formation of a basal conglomerate far up an estuary protected by many rocky islands. On the other hand, a gradual encroachment of the sea on gravel and sand should form just such a deposit.

2. If the wave action had been strong enough to form such a basal conglomerate under conditions of submarine origin of the esker, it seems that the static conditions would have allowed the development of a flatter contact. Such a sloping, irregular contact, however, would be the natural result of a fairly rapid submergence.

3. If the irregular contact of gravel and marine deposits is the product of violent torrents near the mouth of an esker stream in a submerged ice-tongue, there should be some evidence of the cross-bedded gravels and sands of scour and fill, instead of the clean-cut contacts illustrated; also the erosion channels formed under those conditions would seem less likely to be at right angles to the axis of the esker.

4. Fossils occur even in the basal conglomerate of plate 13, figure 2. If this had been formed by wave action immediately on the disappearance of the ice, would life have been present at once, even in a fauna of Arctic affinities? Especially convincing is the occurrence, just a few feet above the base of the clay, at locality 3, of four species of plants, represented by fairly well preserved leaves. These are typical of climatic conditions much the same as exist today in this region, and it hardly seems likely that such conditions could have been restored so soon after the ice had melted from an area as large as that covered by the marine clays of this part of Maine.

5. A lowering of the sealevel on the withdrawal of the water locked up in the ice-sheet and a re-advance of the sea as this water was gradually

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[4] Professional Paper 108, U. S. Geol. Survey, pp. 26, 27, and summary.

[5] Op. cit., p. 24, evidence 4.

restored by melting during the retreat of the ice, as is advocated by many,[6] would be likely to have allowed subaerial erosion of glacial gravels, with a fairly rapid encroachment by the sea as melting progressed.

The above considerations make it seem probable that such illustrations as plate 13, figure 2, and plate 14, figures 1 and 2, represent subaerial erosion in this area. That the point is not absolutely proven is well realized.

The presence of ice-floated boulders in the clay shows that local glaciers, at least, still persisted as far south as the headwaters of the Kennebec.

There seems to be evidence that the period of subaerial erosion was short and submergence comparatively rapid. This conclusion is based on two observations. The first is seen in the character of the erosional unconformities, as shown in the photographs referred to above. Several small undulating erosional surfaces would not be likely to persist in loose, coarse gravel for any length of time. Second evidence, which seems to point in the same direction, is seen in plate 15, figure 1. Here a fragment of sand is inclosed in the upper gravel of the esker. The gravel, which is elsewhere almost horizontally stratified when seen from this angle, here dips in rapidly toward the sand inclusion from all sides and lies in confusion over it. The sand is similar to that immediately overlying the gravel elsewhere and grading into marine clay above. In all probability it is a fragment of marine sand. The only explanation occurring to me is that an ice fragment became embedded in the esker, and that its melting allowed gravel from the side and compact sand from above to fall into the cavity. Since the area affected is less than 10 feet across, the time in which the ice fragment persisted and also the time before the deposition of the sand must have been short.

The chief difficulty in connection with the marine clay and sand is the question as to their upper boundary. As near as the writer can determine, their upper level in this vicinity is just below 160 feet. In several places, especially between Winslow and Benton, across the river from Waterville, it was found that ledge usually rose through the clay very near the 160-foot contour line. Nothing of the character of a cross-section could be found there, however, to show the relationship. During the final work on this paper a new exposure was found along the Maine Central Railroad tracks about one-half mile above Benton. Here the tracks had crossed a slate ridge at a high grade. To lower this it was necessary not only to cut down the ledge, but also a long approach to it,

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[6] For a recent statement of this theory in regard to the "Leda" clay see W. A. Johnston: "Late Pleistocene oscillations of sealevel in the Ottawa Valley." Canada Department of Mines, Ottawa Museum Bulletin 24, 1916, p. 13.

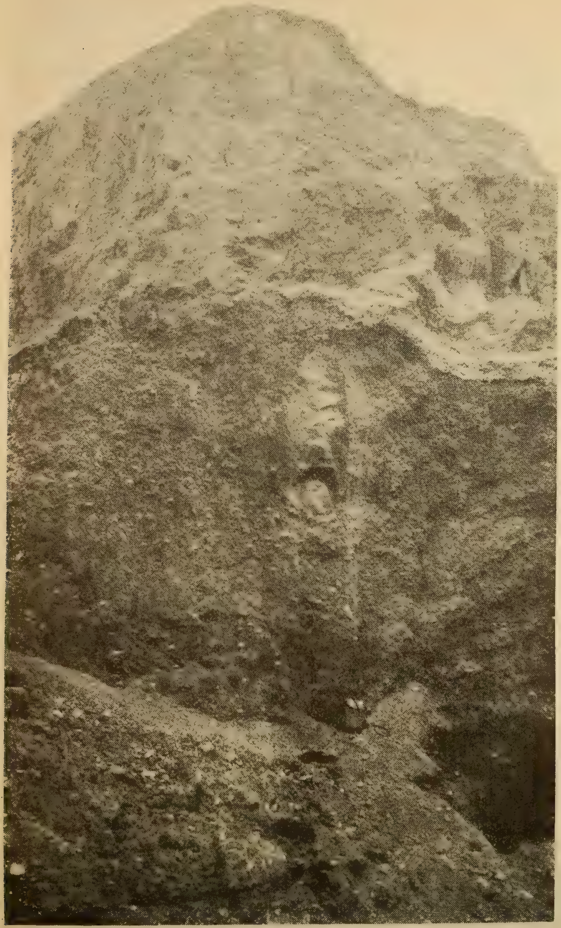

FIGURE 1.—BARTON'S GRAVEL PIT, WATERVILLE, LOCALITY 4

Note the sand inclosed by the gravel. This is thought to represent an old kettle hole (see text). This has been entirely dug away since the photograph was taken.

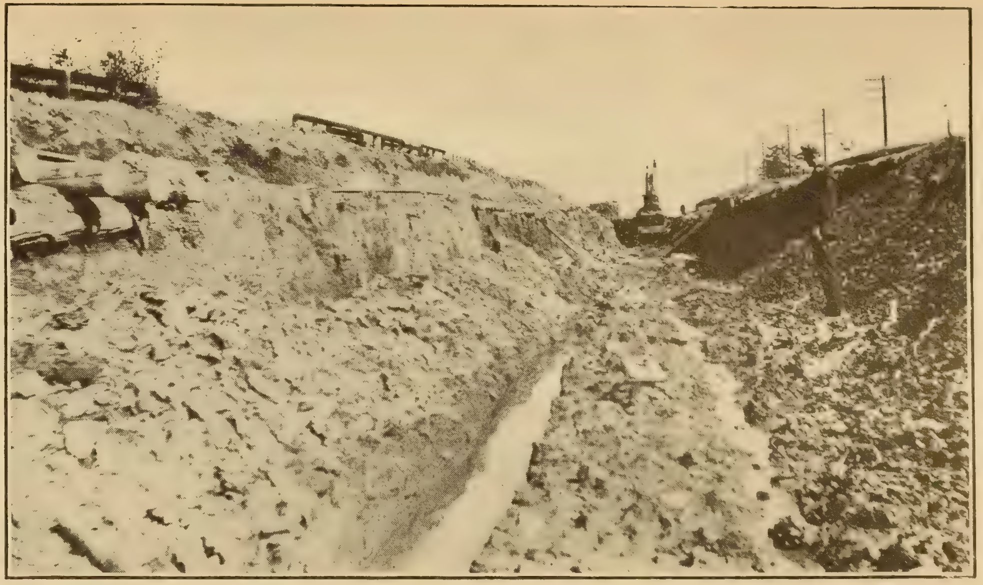

FIGURE 2.—SECTION IN RAILROAD CUT, ONE MILE NORTH OF BENTON, LOCALITY 1

The ditch in the foreground is in fossiliferous marine clay. The drilling machine in the background, and at a higher level, is working in early Paleozoic slates

SECTIONS AT WATERVILLE, MAINE, AND VICINITY

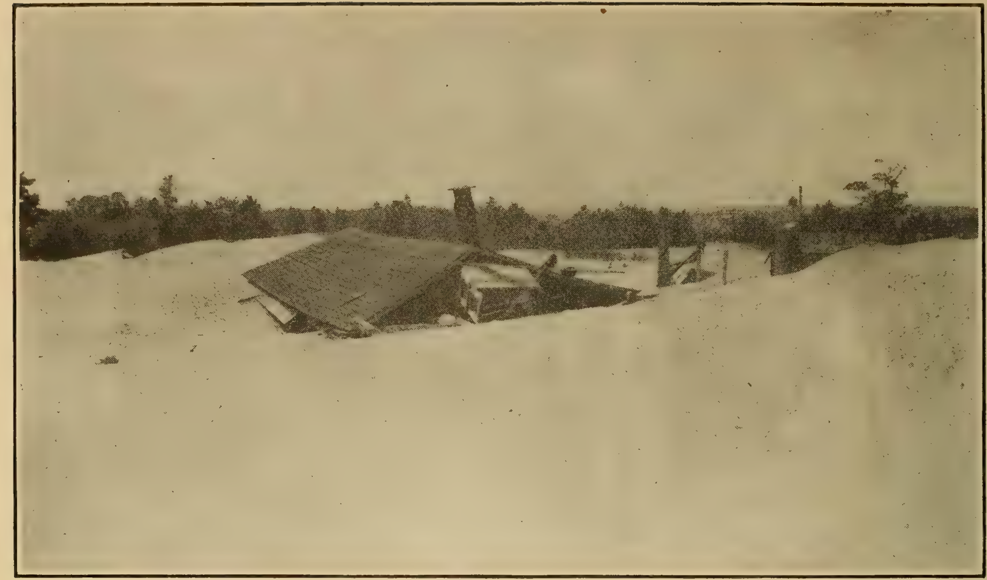

FIGURE 1.—SCENE THREE MILES NORTH OF WINSLOW, MAINE, LOCALITY Z

Shed and grass land destroyed by dune sand. Said to have been started by the opening of a sand pit about 10 years ago

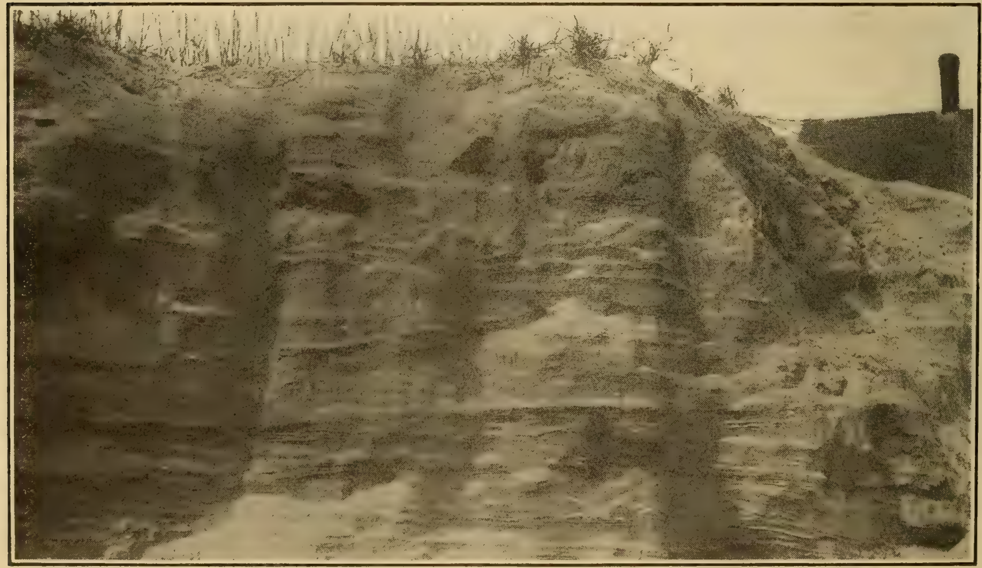

FIGURE 2.—SECTION AT WINSLOW, MAINE, LOCALITY W

Shows the dunelike character of some of the sands

SANDS OF THE OLDER SAND-CLAY SERIES

as shown in plate 15, figure 2. The trench in the foreground is in fossiliferous clay, while the drills are working in slate ledge. The two meet at an altitude of about 160 feet.

There are, however, areas of clay at levels of 200 feet or over. It has been suggested that these are of either fluviatile or marine origin. It is my opinion that in this area, at least, they are of glacial origin and should be mapped as till above the 160-foot level. Owing to the large amount of clay in this till, its general similarity to the clays below, its high altitude, and continued cultivation, there is no topographic feature to mark the boundary between these two formations. However, it is my experience that in most cases there will be more boulders present above the 160-foot level, or else there will be large stone heaps showing a large amount of clearing over what may seem to be a rather level clay plain. In one case I saw several granite boulders, 2 feet or more in diameter and deeply striated, which had recently been removed from one of these higher clay plains. I can, however, offer no conclusive evidence as to the origin of these clays.

PHYSICAL CHARACTER OF THE CLAY

According to Sawyer, who examined the foundation for the Waterville High School when the building threatened to sink in the "quicksand"—that is, the marine clay—"the principal component is an impalpable gray powder with the characteristics of feldspar. Therefore the sample is not a true clay, but owes its claylike properties to being composed of very finely divided rock flour, mechanically ground from feldspathic rocks, such as granite or the metamorphic slates and schists." The boring from which these samples were taken passed through about 70 feet of this clay, ending in fine to coarse sand.

Fossils are fairly common in good exposures of the clay and in places are abundant. They may occur merely as casts or with the shell substance preserved. In this latter case the epidermis may still persist (*Portlandia glacialis, Mytilus edulis, Astarte elliptica,* and *Astarte striata*), and even the elastic ligament (*Astarte elliptica*). These fossils will be described more fully later in the paper.

The marine clays either grade or change abruptly into sands. Where the clay overlaps the esker gravels, the clay may disappear entirely toward the summit of the esker, leaving the sand resting directly on gravel. Such is the case in the locality illustrated in plate 13, figure 2. Within 100 feet of the point shown here, and about 5 feet higher, the sands rest on gravel. These sands are very free from loam and blow readily into dunes when the vegetative cover is removed (see plate 16, figure 1). The tendency of these marine sands to form dunes in many parts of the State has long been known, Stone calling attention to it in 1886.[7] It seems likely that when the sand was first exposed by the relative rising of the land it blew into dunes. In plate 16, figure 2, is shown a section in which a very dunelike structure can be observed, which may date from this period. The irregularity of occurrence of the sand may be accounted for by its redistribution through æolian action or by the formation of sand-bars in a rejuvenated area.

THE YOUNGER GRAVELS

At times the marine clays or sands are overlain by gravels varying from a few inches to five feet or more in thickness. No good exposures of these were found except at locality 6, illustrated in plate 17, figure 1. They seem to be somewhat dirtier than the lower gravels; otherwise they are very similar.

Two interpretations seem to me to be possible. One is that they mark a new advance of the ice, such as has been supposed by Clapp and others; the other possibility is that at the close of the marine epoch the tops of the eskers were brought above water by rising of the land, and that the esker gravels were cut into by the waves and spread out along the shore on top of the clay and sand. This view is strengthened by the fact that in many cases, if not in all, the gravels occur on the clays only in the immediate neighborhood of the axis of the esker and are usually lacking on the more level stretches, where the glacial deposits have been more deeply covered by the clay. The frequent mixture of more or less clay with the gravels might be expected under either interpretation. The gravelly nature of the fossiliferous sands at the City Gravel Pit agrees well with the theory of wave erosion as the agency depositing the gravel. This theory is also simpler, as we shall see in the following paragraph that the land must have been rising, relatively, at about this time. In some cases a third and very simple interpretation seems probable. In the railroad cut above Benton, the marine clays on one side of the cut seem to be overlain by gravel. On the other side of the cut there is no clay and the gravels rest directly on the slate. My idea is that in this case and in many similar cases glacial gravel which rested on ledge at a level higher than that of the marine clays has by gradual creep worked down the slopes of the ledge and overridden the clays; thus a deposit apparently older than the clays overlies them. This is borne out by the fact that the gravels do not seem to occur on the flats below. To my

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[7] Am. Jour. Sci., vol. 31, p. 133.

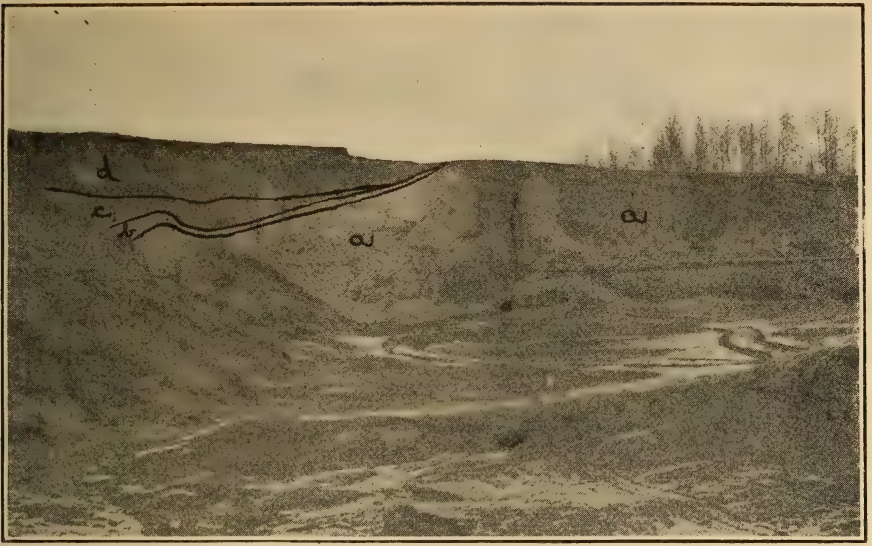

FIGURE 1.—SECTION IN CHAMBERLIN'S GRAVEL PIT, LOCALITY 6

This is the only good exposure of the younger gravels found in this area; *a* = the older gravels; *b*, marine sands; *c*, marine clays; *d*, the younger gravels

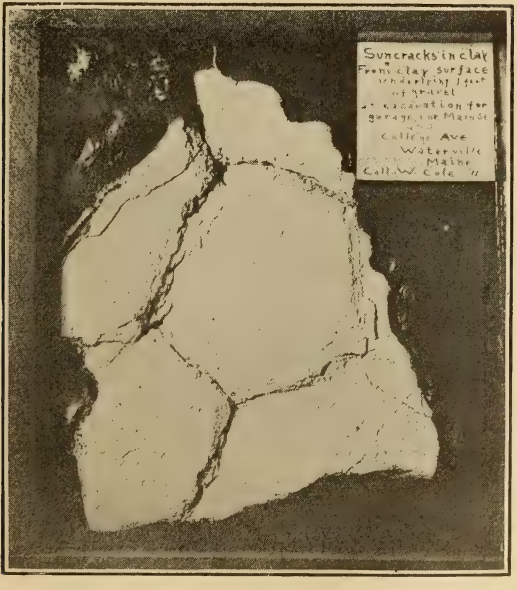
Suncracks in clay
From clay surface
underlying 7 feet
of gravel
at excavation for
garage, cor. Main St
and
College Ave
Waterville
Maine
Coll. W. Cole '11

FIGURE 2.—SUN CRACKS IN CLAY, FROM EXCAVATION FOR GARAGE OPPOSITE POST-OFFICE

The clay lies beneath 7 feet of stratified sand and fine gravel and underlies much of the terrace on which Waterville is situated

FEATURES OF MARINE CLAYS, WATERVILLE, MAINE

mind there is no field evidence of a second ice-advance in the vicinity of Waterville which is not open to one of these alternative interpretations.[8]

THE YOUNGER SANDS AND CLAYS

The younger clays and sands consist of blue clays overlain by coarse, loose, stratified sands, which at times become gravelly toward the base. The clay is massive and exceedingly tough. The sands are fairly well rounded, probably more so than any others of the area. These deposits express themselves topographically in the form of a terrace, only slightly dissected, whose elevation is about 115 feet above sealevel. The larger part of Waterville is situated on this terrace. No fossils have been found in this clay. On the clay surface, at the contact of clay and sand as exposed in cellar foundations, I have found very perfectly developed mud-cracks. An example of these is shown in plate 17, figure 2. The terrace is sometimes sharply, sometimes indistinctly, bounded by a scarp. The best development of the scarp is seen about 100 yards west of the station, where it is fairly abrupt and 40 feet high. The face of this scarp is gravel, covered by fossiliferous marine clay. Not far to the north of here the scarp is ledge, in turn overlain by a similar fossiliferous clay. That the clay of the terrace is younger than the gravel was shown conclusively this past summer when the city ran a sewer line near the base of the scarp, digging through clay; at the same time they were digging gravel from a pit in the scarp, penetrating several feet lower than the near-by clay. The Kennebec River has cut through these clays into the underlying slate and is still actively downcutting.

On the Colby College campus ledge outcrops on the river back of the college at an altitude of 90 feet. A contour map of the campus made the past summer with 5-foot contour intervals shows its highest elevation to be 117 feet. The combined thickness of clay and sand here would probably not be over 25 feet. Excavations for new dormitories penetrated the clay, but did not pass through it. On the other hand, an old well about one-half mile away penetrated over 70 feet of sand and clay. According to my conception, however, this thickness may represent mostly marine clay out of which the terrace was cut, as pointed out in the next paragraph. However, I have never seen anything which seemed to represent a contact of marine clay with the overlying clay of the terrace.

Elevation of the land followed the deposition of the marine clay, gradually bringing it above sealevel. The stream resulting from the withdrawal of the marine waters cut through these clays and perhaps into the underlying slates. If the slates were reached and eroded, this would account for the irregular thickness of the fluviatile clay. If, on the other hand, the slates were not reached, the clays could be explained as river silts, formed by a meandering stream, which had quickly reduced its bed well toward baselevel in the easily eroded marine clays. The irregular thickness would then be due to the unremoved marine clay beneath, which we have already seen was deposited on a very irregular surface. If glacial groovings could be found in the ledge beneath the terrace, it would be evident that this latter case is the true one; but I have found no opportunity to apply this test. Conditions are said to be more favorable for the formation of mud-cracks under floodplain conditions than estuarine, which bears out the opinion that these deposits are of fluviatile origin. The sands overlying them probably mark the beginning of a new land elevation. The streams were rejuvenated and transported coarser sediment, which they deposited in times of flood on top of the clays. Certainly re-elevation brought about the present condition of active cutting through the clays and many feet into the ledge.

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[8] Locality 6 may offer a possible exception to this statement. Here older gravels, clay, and younger gravels come to the surface in a rounded, very drumlin-like form (plate 17, figure 1).

THE FOSSILS OF THE CLAY

As already pointed out, certain parts of the marine clay are quite fossiliferous. The localities where I have found fossils are indicated by numerals in diagram 1. The altitudes above sealevel where the fossils occur, determined by Y level unless otherwise indicated, are as follows:

	No.	Elevation	Stratigraphic position of fossils
Railroad cut, 1 mile north of Benton.	1	139 [9]	About 12 feet from top.
Cellar foundation, first house on Britt street.	2	135.31	Three feet below surface.
City Gravel Pit................	3	123.55 138 [10]	Near the base, near the top, and in sand immediately overlying.
Barton's Gravel Pit...........	4	120.87	About 6 feet above base.
Lockwood Gravel Pit.........	5	139.81	At very base of clay, even into basal conglomerate.
Chamberlain's Gravel Pit.....	6	149 [9]	(?) Only one fossil found.

Of these, the City Gravel Pit has yielded all but one of the species found at the other exposures and many additional ones. For this reason it alone is described in detail. The only thing of special interest in any of the other sections is at locality 5, where the unusually large proportion of barnacles at the base of the clay, even extending downward into the basal conglomerate, deserves mention.

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[9] Determined by aneroid barometer.

[10] Determined by Locke level.

The section shown at the fossiliferous portion follows:

Top	Feet	Inches
9. Sandy clay loam, grading imperceptibly into member below.....	3	..
8. Alternating layers one-eighth to 1 inch thick of sub-angular to angular buff sand and drab clay, with small pebbles scattered throughout, grading into member below.....................	2	6
7. Drab clay, rather sharply separated from member below........	..	10
6. Coarse sand and highly decomposed pebbles of schist, with some well rounded cobbles of quartzite up to 4 inches or more.....	..	4
5. Clay grading into member below............................	..	2
4. Coarse argillaceous sand, much of it highly decomposed rock fragments, grading into member below.....................	..	4
3. Clay, highly fossiliferous (casts only) at top and base, grading into member below.......................................	1	..
2. Sand, sparingly fossiliferous, apparently grading into member below, though with a single layer of scattered, highly weathered, subangular schist and granite cobble near the base......	..	7
1. Massive blue clay, highly fossiliferous in well marked layers, the shells often preserving the epidermis; occasional leaves found; base unexposed.......................................	34	3

This section is chosen because of the unusually good development of the clay. Fifty feet to the north or south this thins greatly, giving a troughlike occurrence to the clay. Members 1 and 2 of the section are those of special interest. Member 2 seemed of interest because it offered the possibility of recognizing a variation of facies in adaption to the sandy bottom. Nothing of the kind could be found, however. Member 1 is most important, for it is highly fossiliferous along certain clearly marked lines. Arthropods are represented by Balanus and the carapace and claws of Cancer (probably the "spider crab"). Several varieties of Gasteropods occur, of which the largest and most striking is *Neptunea despecta tornata;* this seems to be found only in the upper fossiliferous horizon, where it occurs abundantly in a layer just about the thickness of a single shell. Pelecypods are represented most abundantly and in greatest variety. The various fossils found, together with their present ranges, are shown in the following table, prepared largely by Professor Berry:

Astarte elliptica	Cape Cod northward.
Astarte striata	Cape Cod northward.
Asterias sp.	
Balanus crenatus	Arctic to Long Island.
Buccinum cœrulea	
Buccinum cf. *grœnlandicum*..........	

Cancer cf. *irroratus*	
Cardium (Serripes) grœnlandicum	Greenland to Stonington.
Cardium n. sp. (?)	
Cyclina sp.	
Discinisca cf. *atlantica*[11]	
Leda pernula	Arctic to Long Island.
Macoma baltica	Maine to Georgia.
Macoma calcarea	Greenland to Stonington.
Modiolaria discors	Newfoundland to Connecticut.
Mya arenaria	Arctic to Florida.
Mya truncata	
Mytilus edulis	Arctic to North Carolina.
Natica clausa	Grand Manan to Cape Cod.
Neptunea despecta tornata	Off Georges Bank.
Nucula tenuis	Arctic to Hatteras.
Pecten islandicus	Greenland to Connecticut.
Pecten (Amusium) n. sp?	
Polynices grœnlandica	Cape Cod northward.
Polynices heros	Labrador to Virginia.
Saxicava arctica	Arctic to West Indies.
Spirorbis nautiloides	
Trichotropis borealis	Cape Cod northward.
Yoldia (Portlandia) glacialis	Greenland.

Clapp, quoting Packard and Loomis, mentions *Nucula expansa* and *Perpusa lapillus* as also occurring in Waterville. Many of the above, on the other hand, have not previously been recognized from this locality.

The commonest fossil forms at Waterville are *Macoma baltica, Macoma calcarea, Mytilus edulis, Saxicava arctica,* and *Trichotropis borealis.* Viewing the fauna as a whole, cold water species are the most numerous and a few far northern forms are present. The bulk of the fossil forms still exist off the New England coast. Those that are very common today along the Maine coast are *Balanus crenatus, Macoma calcarea, Mya arenaria, Mytilus edulis, Nucula tenuis, Polynices heros, Saxicava arctica,* and *Trichotropis borealis.*

The upper fossiliferous layer of member 1 is at times in a black, very plastic clay with much vegetable matter, which gives it a putrid odor. In connection with this layer have been obtained a few leaves representing, according to Professor Berry, *Populus balsamifera, Ilex verticillata, Gaylussacia dumosa,* and *Vaccinium corymbosum.* These are all species that still live in this area. All have a rather wide range, and the only characteristic northern plant is the Populus, which reaches its southern limit in Maine at the present time. On the other hand, the Vaccinium extends as far south as Virginia, and the Gaylussacia and Ilex reach northern

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[11] Found only at locality 6, and the only species found there.

Florida; so that the climate around Waterville at the time of the deposition of the clays could not have been very different from what it is at the present time.

The mollusks indicate, in general, cold water influenced by melting ice, while the plants indicate a warmer climate—not colder than Maine today. This means that the upper river valleys still contained remnants of glaciers, thus cooling the waters—corroborating the evidence of the ice-borne boulders of the clay—while the climate on the land had warmed up, permitting the return of plants from the south.

Geologic History of the Area

This region, before the advance of the ice, had reached a stage of erosional maturity. The wide valleys, which border the present rejuvenated streams and lie between narrow ridges or knobs of slate rock, bear abundant witness of this fact. The absence of sedimentary deposits between the supposed Eo-Paleozoic slates and the Pleistocene sands, gravels, etcetera, would in itself point to a long-continued erosion interval.

Then came the glaciation, covering the highest hills of the area, wearing off their soil, striating and polishing the resultant rock surface. This is clearly seen wherever ledge is exposed. As the ice retreated, the surface was more or less covered with a sheet of till, and this is now being eroded.

This completes the history of this immediate area, so far as land about 160 feet above sealevel is concerned. Below this level, in the valley bottoms, a more complicated history is revealed. The period when the ice covered the region is represented by the ground moraine of the higher elevations and the fluvio-glacial deposits of the valleys. As the ice retreated the esker deposits were exposed and subjected to erosion. After a comparatively short erosive interval the land was submerged. The encroaching sea picked out the finer particles from the esker gravel and spread them over its slope and the adjoining area. As the sea gradually became deeper the gravels were covered and clays collected in the quiet waters of the estuary. In these waters flourished an abundant fauna nearly identical with that living off the coast at the present day, while the land surface nourished a vegetation which, in respect to the limited flora known, was similar to forms still inhabiting this region.

Icebergs floating down the estuary dropped occasional boulders, which were gradually covered by the clay. These icebergs may have come from the retreating ice-sheet, but because of the lack of decided Arctic affinities in the marine fauna it seems more than likely that the estuary was not fed by the floods of cold water which would come from this, but rather from smaller, local glaciers persisting in the high land toward the sources of the Kennebec. The cirque forming the South Basin of Mount Katahdin is an evidence of such conditions in the headwaters of Penobscot River.

After some time—for the clays are 70 feet thick in places—the land began to rise, resulting in the deposition of sand over the clay. The gravel ridges appeared first and were subjected to erosion; the gravel of their crests was worn off and spread over the sands on their slopes. Then came a period of quiet, and the terrace on which Waterville rests was cut out of the soft clays. The river meandered back and forth across its plain, flooding it at times. As the water receded the silt dried and sun-cracked. Eventually elevation set in again; consequently, when the river overflowed its banks it now left the sands which overlie the sun-cracked clays. In time it cut its channel so deep that it ceased to flood the adjoining plain, and it is still at work actively downcutting. There may have been a temporary pause while a narrow plain now about 80 feet above sealevel was being formed. The water powers of the Kennebec at Waterville are to be considered as due to the fact that a drowned stream, on rejuvenation, failed to relocate its old channel, and not, it seems to the writer, directly due to glaciation.

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DEFORMATION OF UNCONSOLIDATED BEDS IN NOVA SCOTIA AND SOUTHERN ONTARIO[1]

BY E. M. KINDLE

(Read before the Society December 29, 1916)

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PURPOSE OF THE PAPER

Deformation in which a few feet or a few inches of a section have been crumpled and contorted without disturbing the adjacent strata attracted the notice of geologists as early as 1846, when Emmons[2] described the disturbed clays at Albany, New York. Although a number of examples of this phenomenon have been described and various explanations of it offered, the subject appears to be still open to experimental investigation.

It is proposed in this paper to cite two examples of contorted beds which have come under my notice and to describe some experiments which illustrate the principles involved in certain classes of contorted beds.

DEPOSITION AND EROSION IN THE BAY OF FUNDY

Deposition and erosion both proceed with great rapidity on the mud-flats about the estuaries of the Bay of Fundy because of the strong tidal currents and the great volume of suspended sediment in the waters. A considerable part of the load of fine silt is dropped at each flood tide, when the current is at the minimum strength, which is mostly picked up again by the strong ebb currents. The constant shifting of the equilibrium between the two agencies, sedimentation and scour, results in areas in which deposition is dominant and others where erosion is the ruling factor. In the latter areas some interesting features connected with sedimentation are sometimes well displayed. The individual laminæ generally vary between one-eighth and one-quarter of an inch in thickness. Some of the exposures exhibit horizontal beds which have been cut into hollows, which later were filled by sediments in which the laminæ partake of the slope of the hollows which they fill and are thus deflected from a horizontal attitude through their subaqueous disconformable relations.

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[1] Manuscript received by the Secretary of the Society January 29, 1917.
Published with the permission of the Director of the Geological Survey of Canada.

[2] Remarks on the drift period. Am. Quart. Jour. Agric. and Sci., vol. 6, 1847, p. 218.

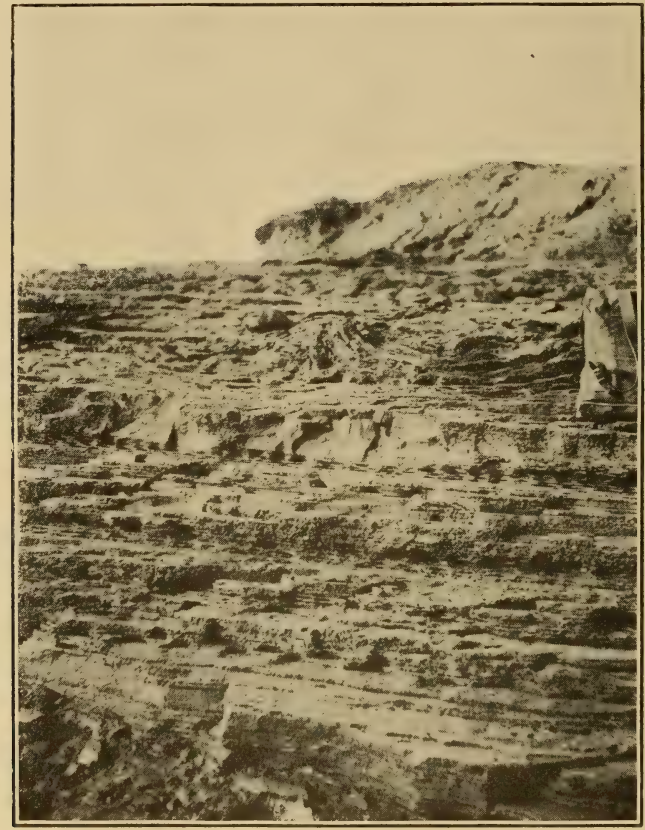

FIGURE 1.—*Section with disturbed Beds between horizontal laminated Silts, Avon River, Nova Scotia*

Irregularity of bedding of a different character which is subsequent in origin to deposition occurs at other localities. The point on the lower side of the junction of the Avon and Saint Croix rivers shows horizontal, contorted, and highly inclined beds, which occur in close relationship to each other (figure 1). The disturbed and contorted beds are here interpolated between horizontal beds (figure 2). Inspection of figure 2 will show a section of finely laminated horizontal silts, which, for a thickness of one foot or more near the middle, have been distorted into a highly convoluted zone. This occurrence of contorted strata in the midst of a series of undisturbed horizontal beds appears to duplicate in unconsolidated sediments certain cases of disturbed bedding between horizontal beds which have been reported in consolidated rocks in the Gaspe Peninsula[3] and in New York.[4] The recent origin of these deformed strata on the Avon River and the present operation in their immediate vicinity of the agencies and conditions under which they must have been produced make the problem of the method of their development much simpler than

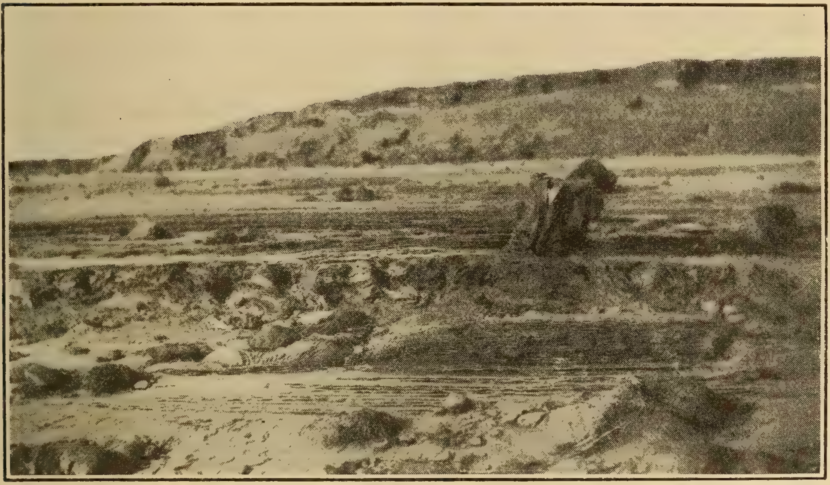

FIGURE 2.—*Contorted Strata between horizontal thinly laminated Clays, Avon River, Nova Scotia*

in the case of the Paleozoic rocks cited above. Its solution should be instructive in explaining such structures in older rocks and merits consideration.

---

[3] W. E. Logan: Geology of Canada, 1863, p. 392, fig. 425.

[4] E. M. Kindle: Note on some concretions in the Chemung of southern New York. Am. Geol., vol. xxxiii, 1904, pp. 360-363.

W. J. Miller: Geology of the Remsen quadrangle. Bull. N. Y. State Museum, no. 126, 1909, pp. 29-33.

Felix F. Hahn: Untermeerische Gleitung bei Trenton Falls (Nord Amerika) und ihr Verhaltniss zu Ahnlichen Storungbilden; Neues Jarbuch fur Mineralogie, etc. Beilage, Band 36, taf. i-iii, 1912, pp. 1-41.

SEDIMENTS OF THE AVON AND OTHER RIVERS

The great bulk of the sediments handled by the estuarine currents of the Avon and other similar Nova Scotia rivers consists of fine silt and sand. Although roughly divisible into these two groups, silt and sand, the estuarine sediments deposited by the currents furnish a considerable variety of muds alone. This variety, as regards consistency or coherence, which depend on water content and fineness of material, can be easily demonstrated by a short walk across any Bay of Fundy mud-flat. On parts of the flats the pedestrian will sink not deeper than his shoe tops; in others he will go in to the knees or hips, and a very moderate journey will disclose still softer mud. It is evident that belts of the very soft mud may be covered by areas of more coherent silt, and that sand deposits several feet in thickness and very heavy may be laid down over some of these very mobile sediments. If a heavy bed of sand were deposited over

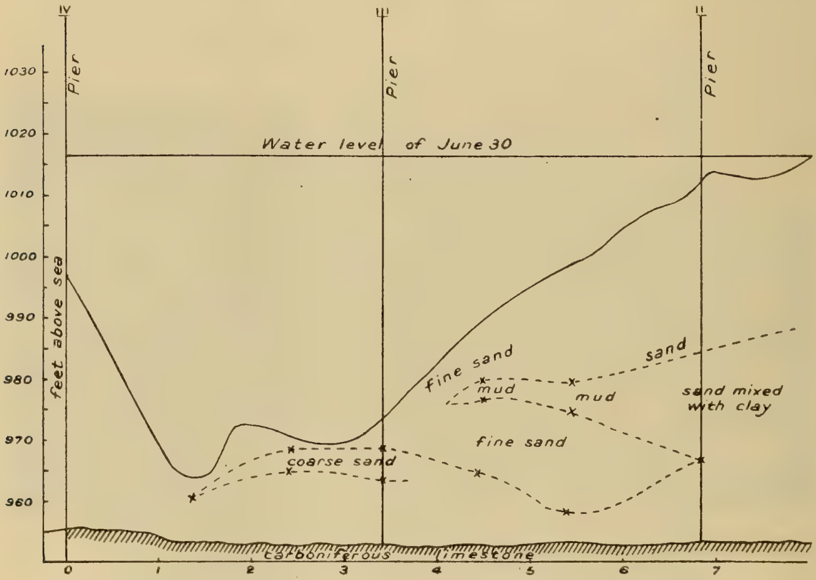

FIGURE 3.—*Bottom Section and Profile of Missouri River at Blair, Nebraska*

Showing potential conditions for horizontal mud-flow. After Todd, Bulletin number 158, U. S. Geological Survey

a portion of an area in which very soft beds were interpolated between more coherent strata, the more mobile beds would be likely to squeeze outward away from the sand pressure toward an unsupported edge, if one were developed by stream or wave cutting. This might occur without disturbing firmer beds above and below through the more yielding character of the soft beds.

Figure 3, which is based on a section of the deposits of the Missouri River at Blair, Nebraska, shows an arrangement of mud and sand beds which will aid in understanding the mechanical conditions under which these soft muds might be sealed between beds of sand which might hold for an indefinite period the potential power of deforming them. A small amount of bottom cutting by the river would expose the mud-beds on the right side of the section and cause them to be squeezed laterally into the river by the heavy sand load above them. Such horizontal movement of the material of the soft mud-beds would inevitably produce deformation of the laminæ consequent on flowage of the beds behind them.

ARTIFICIAL DEFORMATION OF SOFT BEDS

The behavior of soft beds overlain by unequally distributed firmer and heavier beds, as observed in an experimental tank, is instructive in this connection. Marked deformation of the soft beds was thus induced by differential weighting of the firmer upper beds in a small tank. Two beds of clay, each about three-fourths of an inch thick, were deposited over the bottom of the tank by introducing the clay into the partially water-filled tank by means of a tube connected with another vessel used as a reservoir for the thoroughly mixed clay and water. Two thin layers composed respectively of powdered charcoal and plaster of paris, which was much more resistant than the clay beds, were laid on top of the first bed of clay. These show in figure 4 as white and black bands in the lower half of the section. On the level surface of the upper clay bed a delta was formed at one end of the tank by running into it a small stream of sand-bearing water. This delta, as it was formed, sank into and nearly through the upper clay bed, pressing it laterally and considerably thickening it near the sides of the delta. A second delta was made of fine sand at the opposite end of the tank. The bottom-set beds of this delta spread over the entire surface of the clay and of the other sand delta, which had covered but a small part of the clay. The two fan-shaped deltas thus developed covered the middle and sides of the clay bed with a layer of sand one-eighth to one-half of an inch thick, while a small area of the clay at each end of the tank supported a sand deposit one to two inches thick. The sand of these delta deposits, where it is in contact with the side of the tank, shows as a black band above the clay in figures 4 and 5. The inequality of the load of sediment thus placed on the soft clay bed resulted in the unequally weighted clay breaking through the weakest point in the sand-bed covering it and forming a small clay dome or plug extending through the sand, as seen in the photograph, figure 4, directly under the arrow. This occurred at the completion of the second delta. After this photograph was taken the sand load on the clay was considerably increased to a nearly uniform depth over the clay. By means of current scour the sand was then somewhat reduced in thickness at one point, a small tube being used to introduce a stream of water for this purpose. Additional pressure was then placed on the sand by means of a bag of shot. This resulted in the clay slowly rising at the point where the sand load had been reduced on the side of the tank by scour (figure 5). The mass squeezed out through the sand assumed the shape on the upper surface of a steep-sided half dome, the contact with the face of the tank preventing the formation of a complete dome. The plug of clay continued to rise till it was slightly above the surface of the water in the tank. Examination of the photographs shows that marked disturbance

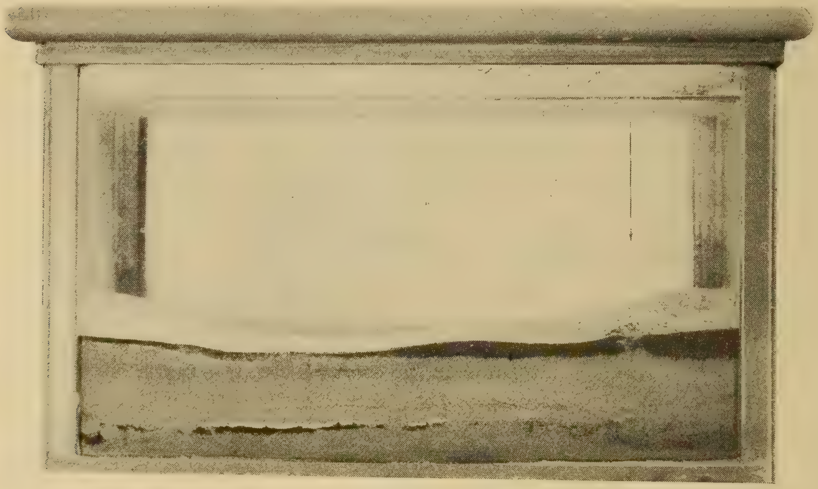

FIGURE 4.—*Stratified Clays deposited from Water in experimental Tank*

Showing "mud lump" and deformation produced by differential weighting of the clay beds with sand. The surfaces of each of the four strata below the sand were perfectly horizontal before the introduction of the sand. Note the great disturbance of the charcoal band in lower half of section and the clay plug pushed through the sand below the arrow.

of the charcoal band occurred in the first stage of the experiment. Later stages show coincident development in different parts of the section of doming and upthrust faulting accompanied by extensive flowage of the subsurface strata.

This experiment duplicates, it is believed, on a small scale the phenomena of the mud lumps[5] which rise in the delta of the Mississippi River a few feet above water level. A river delta affords a particularly favorable field for such phenomena because of the constant interplay of marine and river currents and the resulting continuous shifting of the areal relations of heavy, coarse sediment and those of lighter and more mobile character. While the mud lumps of the Mississippi appear to be unique in rising above the surface of the water, probably through being composed of material sufficiently tenacious to withstand current and wave action for some time, similar phenomena doubtless occur in many other deltas which do not become apparent through failure of the upsqueezed masses to reach the surface of the water. These experiments

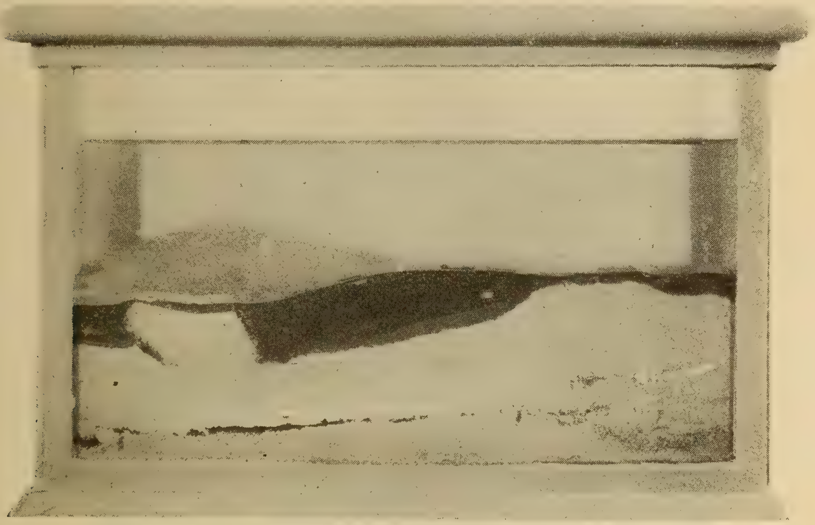

FIGURE 5.—*Another View of the water-laid Beds shown in Figure 4*

This result is obtained after adding sand and shot to the surface load and subjecting the sand cover in the left third of the section to current scour. The thinning of the sand cover, combined with the increased load, developed the upthrust clay plug seen on the left side of the figure.

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[5] G. D. Harris: Geol. Surv. of Louisiana, Rept. for 1899, pp. 119-121; Rept. for 1902, pp. 38-39.
E. W. Shaw: U. S. Geol. Surv. Prof. Paper no. 85B, 1913, pp. 11-27.

show clearly the tendency of soft beds to move in the direction of least resistance, with a minimum amount of disturbance of firmer superposed beds under certain conditions of loading. In the illustrations, numbers 4 and 5, this direction was mainly upward, and its relationship to the phenomena presented by the contorted Nova Scotia beds is not perhaps at first sight evident, since the latter represent horizontal movement of strata. Vertical extrusion, however, of soft beds through breaks in superposed beds may directly induce horizontal flowage of the soft beds toward the extruded material. The irregular or uneven character which such flowage would be likely to assume would disturb in a more or less complex manner the bedding of soft laminated clay mud. Lenticular-shaped beds of soft mud inclosed by firmer beds, if in contact with a thick bed of superposed sand on one side, would under certain conditions give rise to such lateral flowage. One condition which would bring about such lateral migration of extra mobile layers would be current scour, as shown in these experiments, which would remove in one area the stronger superposed beds, causing the soft beds there to squeeze upward, as in figure 5, while elsewhere they flowed toward the base of the plug under pressure

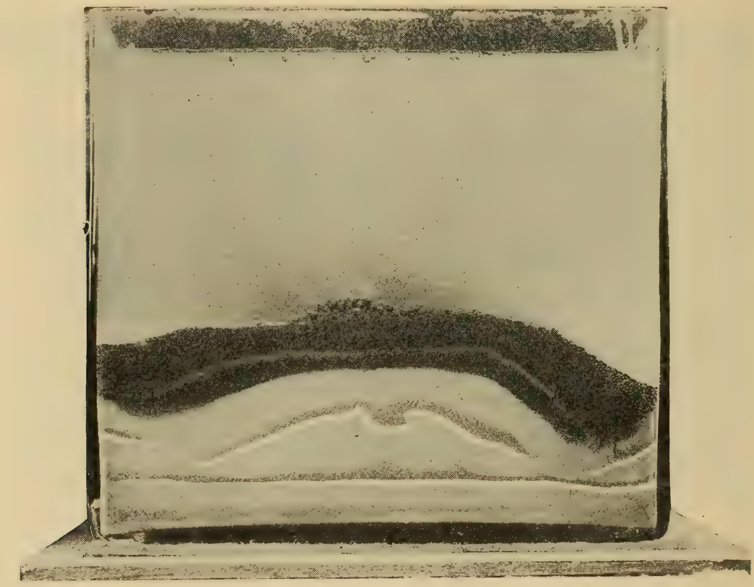

FIGURE 6.—*Glass Tank Section composed of Clay, powdered Chalk, and Sand Strata originally horizontal*

Weighting with shot has deformed the upper without disturbing the lower beds of the heavy sand beds. The experiment just described shows more or less disturbance of the entire thickness of the section.

Another experiment of a similar character to that already described shows that extensive disturbance and lateral movement may be produced in the higher beds of the experimental section with little or no effect on the beds immediately below. Shot was used for weighting the beds shown in figure 6, which represents the second experiment. The beds of clay, powdered chalk, and sand were horizontal at the beginning of the experiment. On one side of the tank in this experiment thrust-faulting was developed in the middle part of the section. In this photograph (figure 6) marked bending of the beds and crumpling of the upper beds is shown, with the lower beds entirely undisturbed. The next figure, number 7, shows a later stage of the same experiment. This experiment duplicates one of the conditions characteristic of the Avon River beds, namely, disturbed beds resting on undisturbed beds. The other essential feature, horizontal beds above the contorted beds, would be supplied by the continuation of the normal processes of deposition laying down horizontal beds after the removal by current scour of the heavier and coarser beds which produced the deformation.

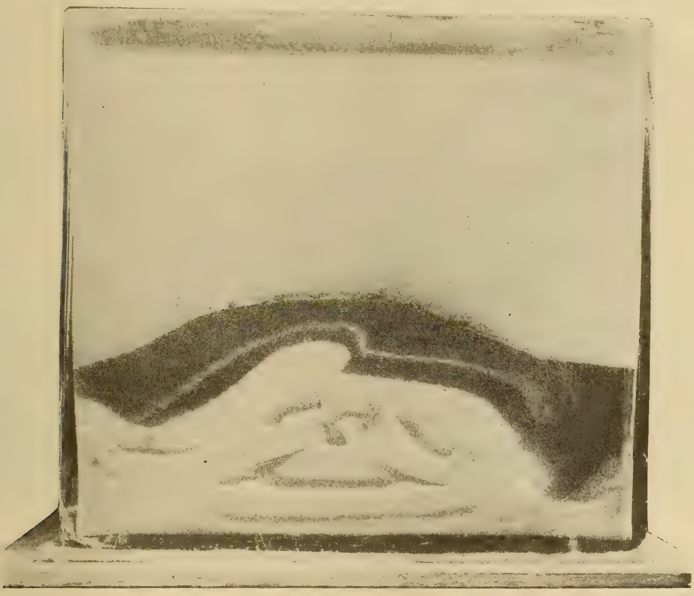

FIGURE 7.—*Later Stage in the Deformation shown in Figure 6*

EXPLANATION OF THE DISTURBED BEDS OF AVON RIVER

The disturbed beds of the Avon River mud flats are believed to have originated through differential weighting of the beds acting in conjunction with bottom scour which operated in the way suggested by the experiments to produce horizontal movement of the beds.

Disturbances of the bedding in strata of sand may originate in the same general way through the juxtaposition of beds of quicksand and ordinary sand. The extreme mobility of the former would be likely to cause readjustment of the layers if a deposit of ordinary heavy sand were laid in uneven thickness on it. Woodworth[6] has described a section at Port Kent, New York, in which the sands have been disrupted by clay, which has penetrated the sand after the manner of irregular dikes.

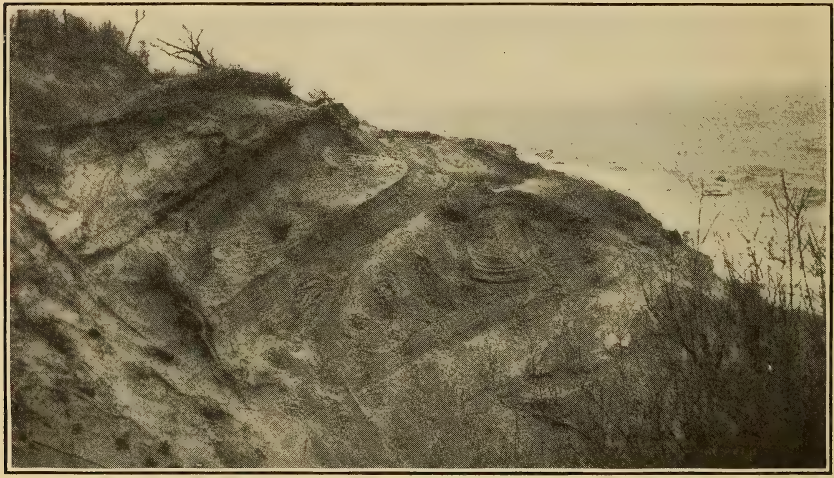

FIGURE 8.—*Contorted Beds of Sand on Shore of Lake Erie west of Port Rowan, Ontario*

THE CLIFFS OF PORT ROWAN, ONTARIO

The cliffs of postglacial sands and clays which border the north shore of Lake Ontario 12 miles west of Port Rowan show a section in which a thickness of beds much greater than those described above have suffered deformation. These beds are composed chiefly of sand and are overlaid by horizontal and cross-bedded sands, as shown in figure 8. They rest on lake clays which probably belong to the Lake Whittlesey stage of sedimentation. The inclination of the beds toward the left is the result of a land slip which has dropped a section of the cliffs 10 to 75 yards wide and several hundred feet long into the waters of the lake. The bed showing disturbed strata has a thickness of 10 or 12 feet.

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[6] N. Y. State Mus. Bull. no. 84, 1905, p. 189, fig. 23.

In seeking the cause of the highly inclined and disturbed condition of the strata, which at one point simulate the outline of a heart-shaped figure, the history of these beds should be considered. They were laid down when Lake Erie was held at a level more than 100 feet higher than at present by the Lake Whittlesey ice-barrier. While the beds of this section were being assorted and shifted into their present position by wave and current action, large icebergs and extensive fields of floating ice were characteristic features of the surface of Lake Whittlesey, in which these beds were laid down. At this stage of its history Lake Erie must have displayed in summer fields of floe-ice and icebergs quite comparable to those which today border the Greenland coasts in early summer. Any one who has seen an Arctic ice-pack moving majestically and with immeasurable force before the wind needs not to be told that an ice-pack when it grounds before a gale is capable of plowing up and disturbing in a very extensive fashion any unconsolidated beds on which it may be driven by the wind. Various observers have testified to the efficiency of grounded ice in disturbing bottom deposits on Arctic coasts. Quotations in this connection from two of these will suffice.

Lieut. Charles H. Stockton, of the United States Navy, thus describes the action of this ice when it is driven ashore:

> "Sometimes a long line of heavy floe-ice from the pack grounds in the shallow water near the shore during northerly winds, pressed from behind by the force and the weight of the entire northern pack. It is gradually forced up, plowing its way through the bottom, at the same time rising gradually along the ascent of the bottom toward the land." [7]

Lieutenant Stockton made a hydrographic survey of the anchorage near Point Barrow, in which he

> "demonstrated that the contour of the bottom is constantly changed by the plowing and planing done by the heavy ice grounded and driven up by the pressure of the mighty ice-pack, under the influence of northerly winds and gales." [8]

The Lake Whittlesey ice-barrier which stretched along the north border of the lake but a short distance north of the section under consideration must have sent into the lake innumerable tongues of glacial ice, which before breaking up into bergs were unquestionably efficient agents in plowing up the bottom sands and clays and doubtless produced many examples of disturbed bedding comparable with that shown in figure 8. The entire competence of ice, acting either as grounded fields or as tongues of glacial ice, to produce the disturbed bedding seen in the Lake Erie section west of Port Burwell, together with the great thickness and extent of the ice-fields which must have characterized the surface of Lake Erie during an early stage of its history, appear to justify the reference of this phenomenon to ice-action.

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[7] Charles H. Stockton: Nat'l Geog. Mag., vol. ii, 1891, pp. 182, 183.

[8] Ibid., p. 182.

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SUBMERGED "DEEPS" IN THE SUSQUEHANNA RIVER[1]

BY EDWARD B. MATHEWS

(*Read before the Society December 28, 1916*)

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INTRODUCTION

Prior to the construction of the dam and power plant at McCalls Ferry, Pennsylvania, a careful survey of the river bottom was made by soundings under the direction of Mr. Cary T. Hutchinson, Chief Engineer of the McCalls Ferry Power Company. The results of this survey, so far as they were of scientific interest, were placed at the disposal of the writer, who, as consulting geologist, made an examination of the river bottom laid bare by the construction of the coffer dam. The portion of the survey under present consideration extends from Turkey Hill, 3 miles south of Washingtonboro, Pennsylvania, to tide near Port Deposit, Maryland. Throughout the entire distance the river flows in a flat-bottomed rock gorge with stream-cut walls, which rise to the general level of the Piedmont Upland. The river bottom is generally studded with numerous rocky inlets, which rise but a few feet above the normal river surface, and a few steep-sided islands, whose wooded tops may reach 100 feet above the water. Under ordinary conditions the bed of the river is covered with less than 15 feet of water, and in dry season may be largely exposed as a rock floor from one-half to one and one-half miles in breadth. Within this flat bottom of the broad gorge the survey discovered (figure 1) six long spoon-shaped depressions, some of them over 100 feet deep, with their deepest portions extending below tide level. To record the position and character of these "deeps," and to show that the usual explanations for similar phenomena do not apply, is the purpose of this paper.

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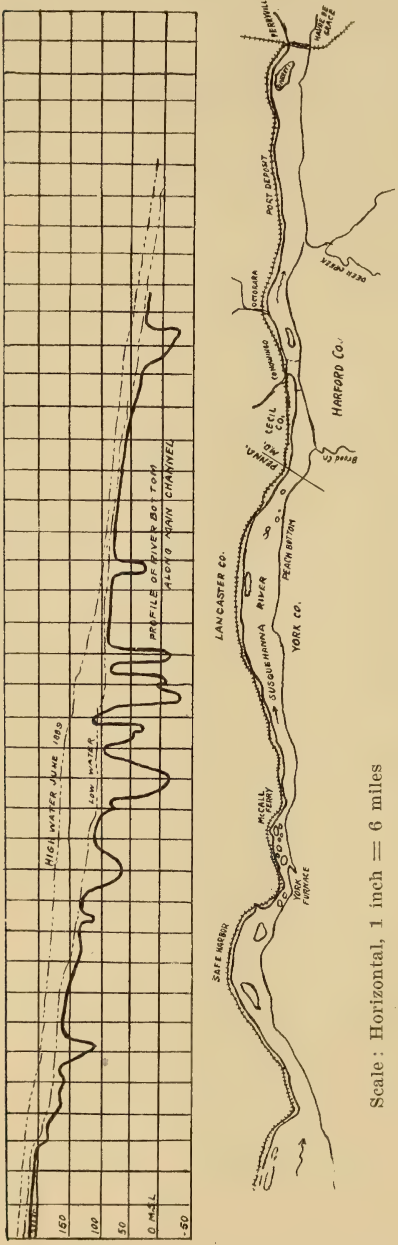
[1] Manuscript received by the Secretary of the Society February 19, 1917.


PERRYVILLE
HAVRE DE GRACE
PORT DEPOSIT
OCTORARA
CONOWINGO
CECIL CO.
PENNA.
MD.
HARFORD CO.
DEER CR.
BROAD CR.
PEACH BOTTOM
LANCASTER CO.
SUSQUEHANNA RIVER
YORK CO.
McCALL FERRY
YORK FURNACE
SAFE HARBOR
PROFILE OF RIVER BOTTOM ALONG MAIN CHANNEL
HIGH WATER JUNE 1889
LOW WATER
150
100
50
0 M.S.L.
-50

Scale: Horizontal, 1 inch = 6 miles

FIGURE 1.—*Plan and Profile of Susquehanna River, showing Location of "Deeps"*

GEOLOGY OF THE REGION

The geology of the region on either side of the Susquehanna gorge from Columbia, Pennsylvania, to Havre de Grace, Maryland, may be briefly summarized as an overthrust block or series of blocks of Precambrian schists and gneisses resting on less metamorphosed limestones and shales of Cambrian and post-Cambrian age. The forward end of this thrust forms an irregular line, crossing the Susquehanna River at Turkey Hill, below Columbia, and continuing thence eastward in a sinuous line to Quarryville and the Chester Valley.

This block consists of several fragments, separated by faults, and near its northwestern edge are several "fensters," through which appear portions of the underlying

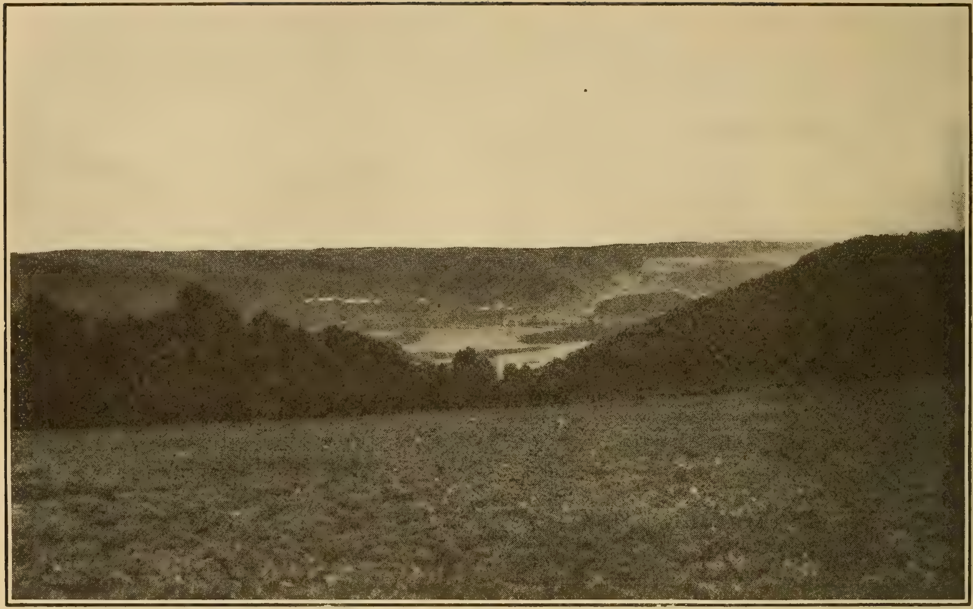


FIGURE 1.—GENERAL VIEW OF UPLAND PENEPLAINS AND INCISED FLAT-BOTTOMED GORGE OF SUSQUEHANNA

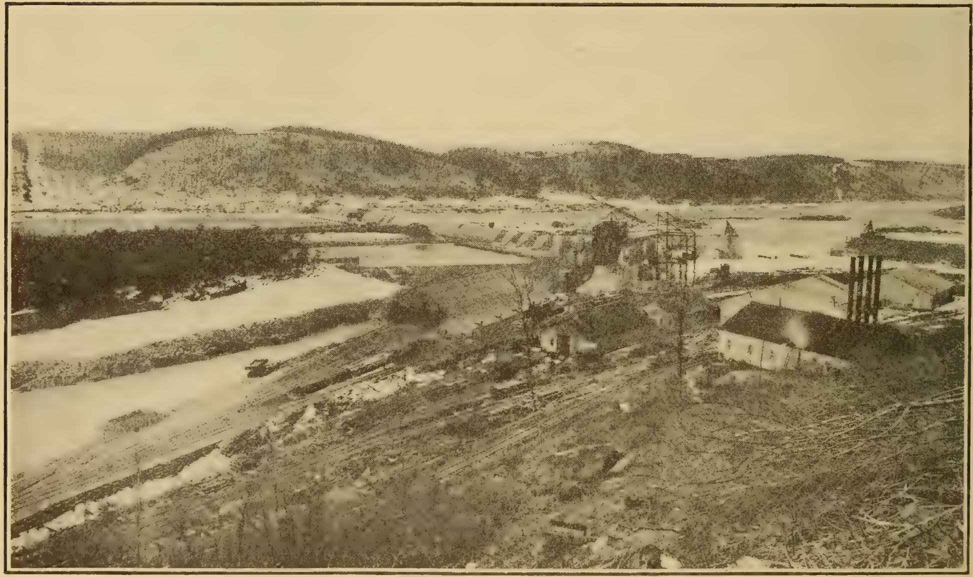


FIGURE 2.—VALLEY FLOOR EXPOSED DURING CONSTRUCTION OF DAM, SHOWING "DEEP" AT LEFT

VALLEY OF SUSQUEHANNA RIVER AT MC CALLS FERRY, PENNSYLVANIA complex. One of these, exposing an impure limestone, is crossed by the Susquehanna at Shenks Ferry, but is apparently without influence on the profile or plan of the river valley.

The rocks composing the overthrust block are micaceous schists and gneisses and metamorphosed eruptives. With minor exceptions, they seem to offer the same degree of resistance to the erosion of the river. The outstanding salients of the gorge do not correspond with noticeable differences in the character of the rock, but are largely determined by the entrance of side streams, which away from the gorge flow back and forth over geological boundaries little influenced by the differences in the resistant qualities of the underlying formations.

The schistosity and possible bedding of the rocks strike across the gorge and dip at steep isoclinal angles for miles at a stretch. The geologists of the Second Pennsylvania Survey noted an anticlinal fold crossing the river above McCalls Ferry in the vicinity of Torquan Creek, and later studies on both sides of the river have adduced evidence of a series of open folds in accord with the Appalachian structure to the north and west.

The surface of the thrust-block and the underlying formation, where exposed, show the Somerville, Harrisburg, and older plains. These, however, are not well shown on the sides of the gorge, though readily recognized along the side valleys and in the upland area on either side of the river (the apparent single plain shown in plate 18, figure 1, is in reality composed of several plains at different elevations, as may be seen from a study of the topographic maps). At a few points, as near Washingtonboro, Pennsylvania, and Wildcat Point, Maryland, there are cappings of "high-level" gravels. Below the Somerville plain are evidences of one or more still later incipient baselevelings in the level rock floor of the river itself and the low-lying islands and contiguous rock flats. These latest beginnings of baselevels are provisionally called the Susquehanna baselevel for convenience, although it is clearly recognized that they include little more than local widenings of the floor of the gorge. It is in the latest of these plains that the river has cut the "deeps" which form the subject of this paper.

Detailed Description of the "Deeps"

LOCATION OF THE "DEEPS"

The well defined "deeps" disclosed by the careful hydrographic survey of the river bottom conducted by the McCalls Ferry Power Company are located respectively 1$\frac{3}{5}$ miles above Safe Harbor, above the dam at Mc-

Calls Ferry, at Mingua (between the dam and Culleys Falls), below Culleys Falls, and on the west shore near Conowingo, Maryland. Only one of these, that at Mingua or Holtwood, was well exposed during the construction period. The details of these "deeps" are as follows:

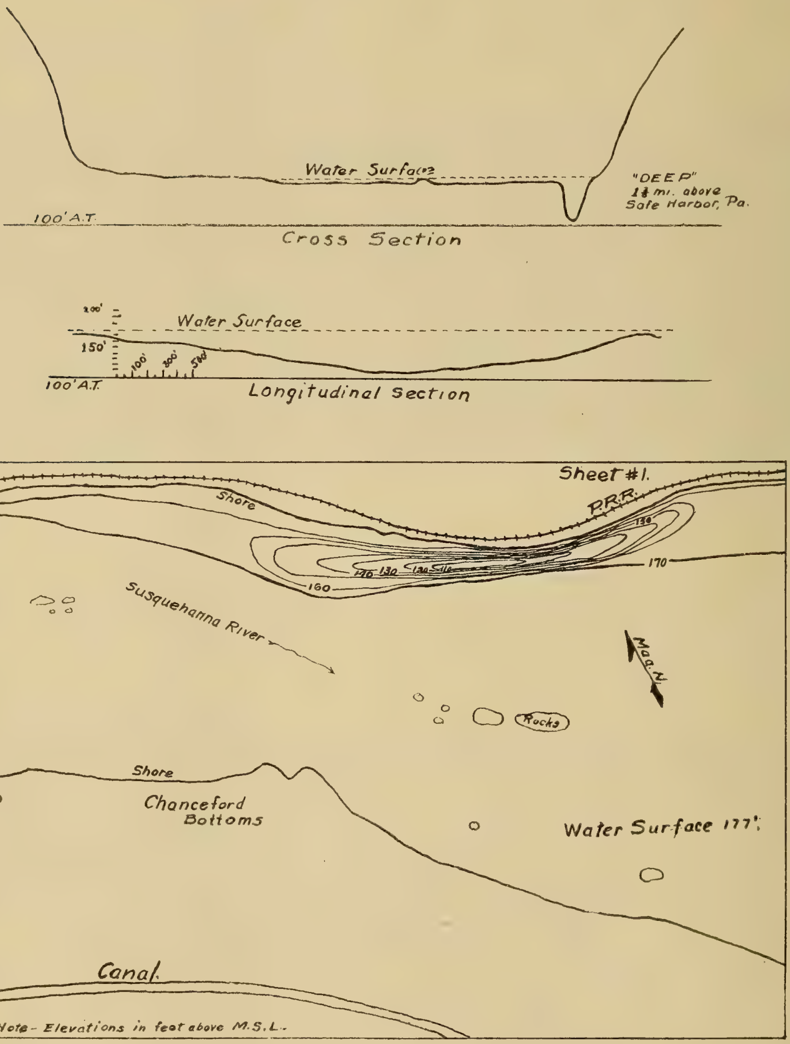

Water Surface
"DEEP"
1¾ mi. above
Safe Harbor, Pa.
100' A.T.
Cross Section
200'
Water Surface
150'
100
200
300
100' A.T.
Longitudinal Section
Sheet #1.
Shore
P.R.R.
130
170
140
130
130
140
160
Susquehanna River
Mag. N.
Rocks
Shore
Chanceford
Bottoms
Water Surface 177'.
Canal.
Note- Elevations in feet above M.S.L.

FIGURE 2.—*Map and Profiles of "Deep" in Susquehanna River above Safe Harbor, Pennsylvania*

Scale: Horizontal, 1 inch = 1,200 feet; vertical, 1 inch = 300 feet

ONE AND THREE-FIFTHS MILES ABOVE SAFE HARBOR, PENNSYLVANIA

This lies near the east or left bank of the river opposite the Chanceford bottoms. The water surface is about 177 feet above tide and the rock bottom of the gorge between 180 and 170 feet above tide. The "deep" is a narrow depression, 3,200 feet long and 150 feet wide at its deepest point, which is 60 feet below the level of the rock bottom. The depression widens upstream to 400 feet and extends as a shallow trench for an additional 1,700 feet.

The rocks exposed on the banks are micaceous and chloritic schists and gneisses in which the schistosity strikes north 70° east and dips about 20° upstream. They show no differences in resistance competent to localize a strong waterfall.

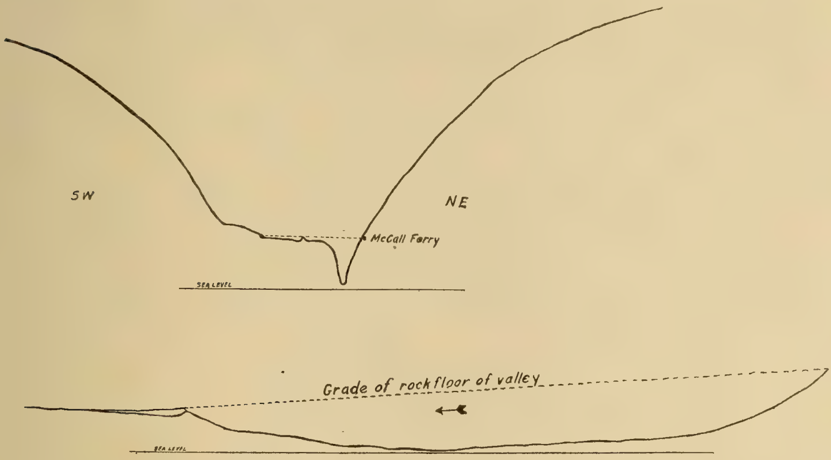


FIGURE 3.—*Profile of "Deep" above Dam at McCalls Ferry, Pennsylvania*

Scale: Horizontal, 1 inch = 2,000 feet; vertical, 1 inch = 500 feet

The profile across stream shows (figure 2) a steep gorgelike depression incised in the U-shaped valley of the river. The longitudinal profile is a gentle catenary curve, slightly steeper downstream.

"DEEP" AT MC CALLS FERRY

This "deep" lies just above Fry Island, the site of the dam, and extends upstream for a distance of nearly 2 miles. The water surface was originally 125 feet above tide and the rock floor along its edges about 115 feet. The bottom of the larger hole lies at 15 feet below sealevel, or at a depth of 125 feet below the rock rim of the depression. The details of the shape and profile of this hole are lacking (through loss of records) beyond this fact, that near its upstream end there is a subordinate depression, about 25 feet below the normal profile of the hole, which makes the upstream gradient of the depression less than that of the downstream.

The rocks along the bank are micaceous and chloritic schists and gneisses in which the schistosity strikes north 70° east and dips 30° downstream. They show no noticeable differences in resistance to account for the depression. In the narrows above McCalls Ferry the banks rise abruptly for 400 feet above the river, but the crest of the harder ridge does not conform to the strike of the rocks, since the western rampart lies upstream. The extension across stream on the strike of the rocks shows side valley opposite promontory, and the reverse and not a strike ridge cut by the river.

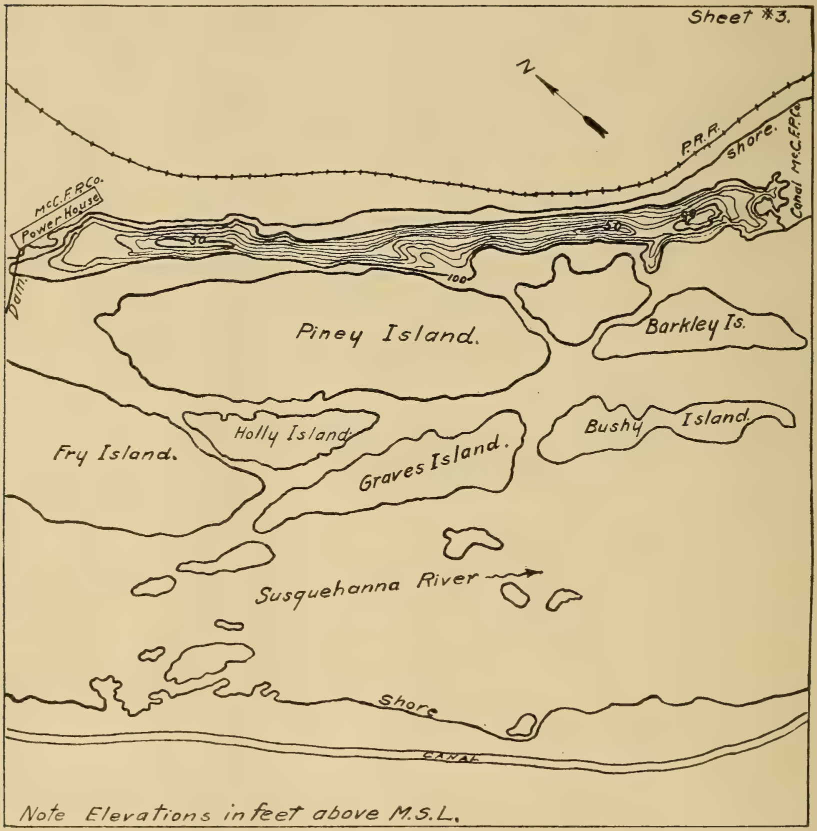

Sheet #3.
N
P.R.R.
Shore.
Canal McC.F.P.Co.
McC.F.P.Co.
Power House
Dam.
50
50
50
100
Piney Island.
Barkley Is.
Holly Island
Fry Island.
Graves Island.
Bushy Island.
Susquehanna River
Shore
CANAL
Note Elevations in feet above M.S.L.

FIGURE 4.—*Map of "Deep" at Holtwood, Pennsylvania*

Scale: 1 inch = 1,000 feet

MINGUA OR HOLTWOOD

This "deep" lies close to the left bank of the Susquehanna, between it and Piney Island, and has been utilized by the engineers as a tail race for their power plant. During the construction of the dam it was exposed by a diversion of the water to a depth of nearly 50 feet. The water surface was about 110 feet above tide and the rock floor about 100 feet. From the latter rise Fry and Piney islands to a height of 140 and 160 feet respectively. The hills above the power plant rise rapidly to an elevation of over 500 feet. This depression is a gorge of 4,000 feet long, with a width of from 200 feet to 300 feet within the rock floor of the river, which at this point is about 100 feet above tide. The general level of the bottom of the gorge is 60 feet above tide, or 40 feet below its rim, and shows three local depressions (figure 4). That opposite the upper end of Piney Island reaches to 50 feet above tide, while the two at the lower end, opposite Barkley Island, reach 40 feet above tide. The rock barrier between it and the foot of Culleys Falls was removed, so that it is now continuous with the "deep" described later. The withdrawal of the water gave exceptional opportunity for studying the walls. Everywhere were deep vertical pot-holes of varying diameter and perfection, so closely placed that they suggested the fluting of a pipe organ or the fracture of a block by the use of "plug and feathers." Some of the pot-holes extended

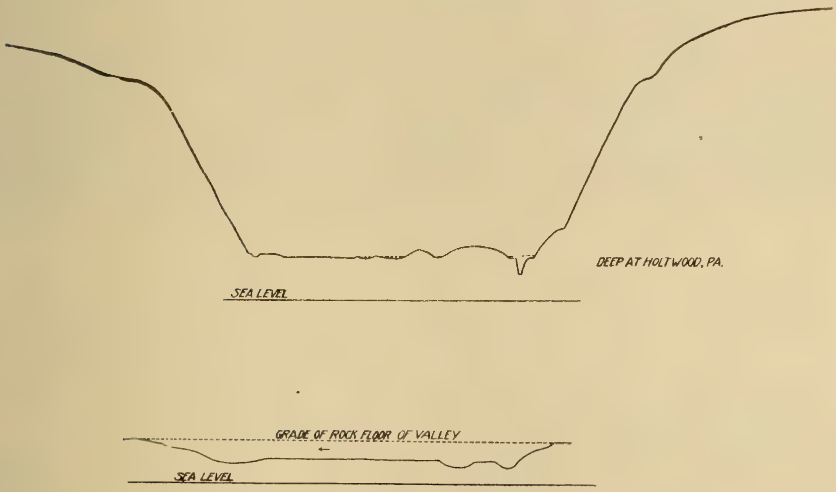


FIGURE 5.—*Profiles of "Deep" at Holtwood, Pennsylvania*

Scale: Horizontal, 1 inch = 2,000 feet; vertical, 1 inch = 500 feet

below water level, while others showed nests of boulders part way down the sides of the gorge. The general character is shown in plates 19 and 20.

BELOW CULLEYS FALLS

The "deep" below Culleys Falls is cut in the level rock bottom of the river, which is here 100 feet above sealevel. It is situated close to the left bank of the river, between it and the Bare Islands, which rise 70 feet above the river. It is approximately 7,200 feet long, 250 feet wide, with three depressions—the first 130 feet deep, the second and third 100 feet deep, separated by a 25-foot ridge. The deepest of these holes lies between the shore and Wolf Island, where the east channel is the entire width of the depression. In longitudinal section (figure 5) these "deeps" show the usual downstream sag in the bottom profile. The rocks are chloritic and mica schists striking north 70° east and dipping southeast. There is no connection apparent between these deeps and Muddy Falls, which empties into the river at this point.

ABOVE FITES EDDY

Between Sicily Island and the left bank of the river, 1,000 feet above Fites Eddy Station, is a "deep" 3,400 feet long, which shows a well defined terrace 30 feet below the valley floor and 70 feet above the bottom of the "deeps." The breadth is here less uniform, the chasm varying from 500 to 150 feet from rim to rim. The deepest portion is practically level at an elevation of 10 feet above tide for a distance of 1,000 feet. The rocks are chloritic and micaceous schists with the usual strike and dip. The islands, with levels at an elevation of approximately 100 feet, suggest remnants of the peneplain analogous to the Wicomico terraces in Maryland.

ORIGIN

Similarly appearing "deeps" in beds of rivers have been frequently encountered and described. Their origin has usually been ascribed to some form of "cliff" waterfall, as where the stream flows over the edge of a hard horizontal stratum or down a crevasse in the ice, or over some resistant stratum or dike. Apparently none of these explanations fits the present case. The region is south of the former continental ice-sheets, and the cuttings and pot-holes cannot, therefore, be ascribed to the action of subglacial streams and waterfalls. The rocks show practically vertical position and therefore can not have been produced by a fall due to the

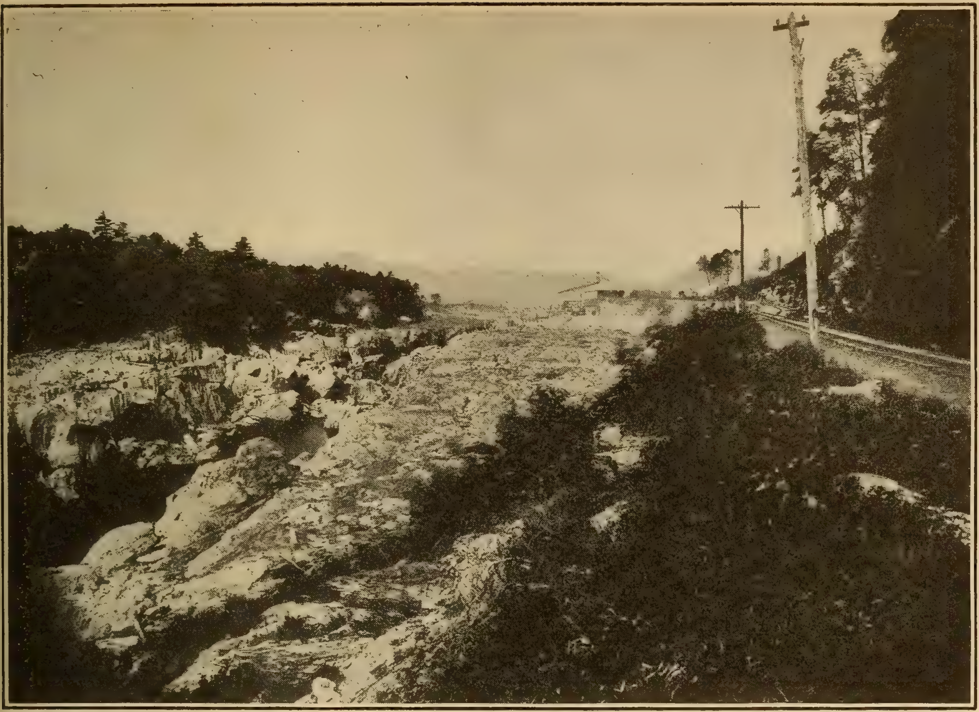


FIGURE 1.—FLAT ROCK-FLOOR AND "DEEP" EXPOSED, LOOKING UPSTREAM

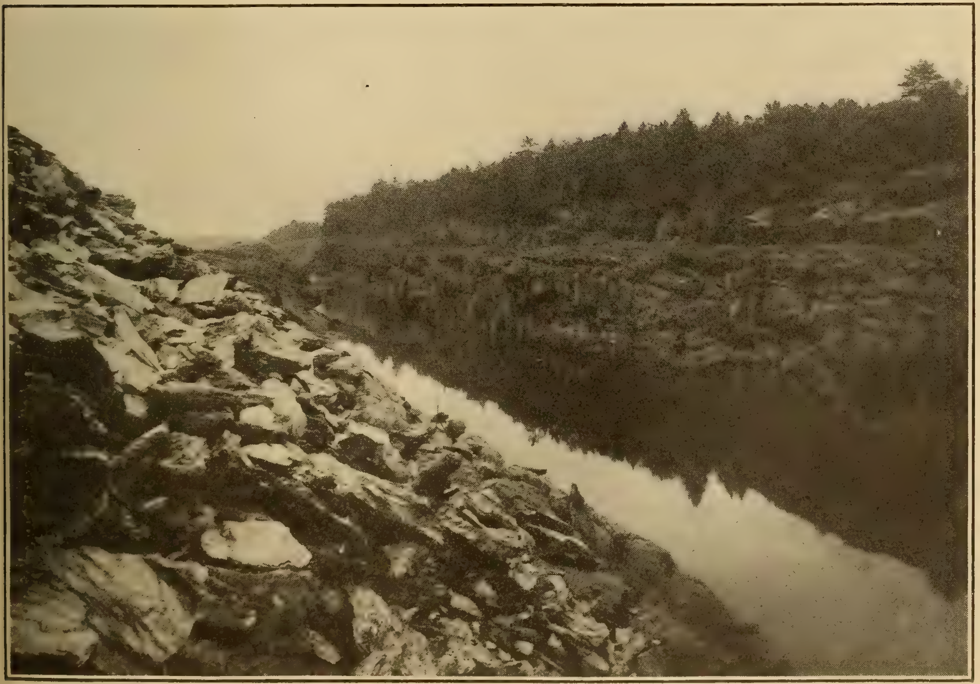


FIGURE 2.—DEEP PARTIALLY DRAINED, LOOKING DOWNSTREAM

NEARER VIEWS OF "DEEP" AT HOLTWOOD, PENNSYLVANIA

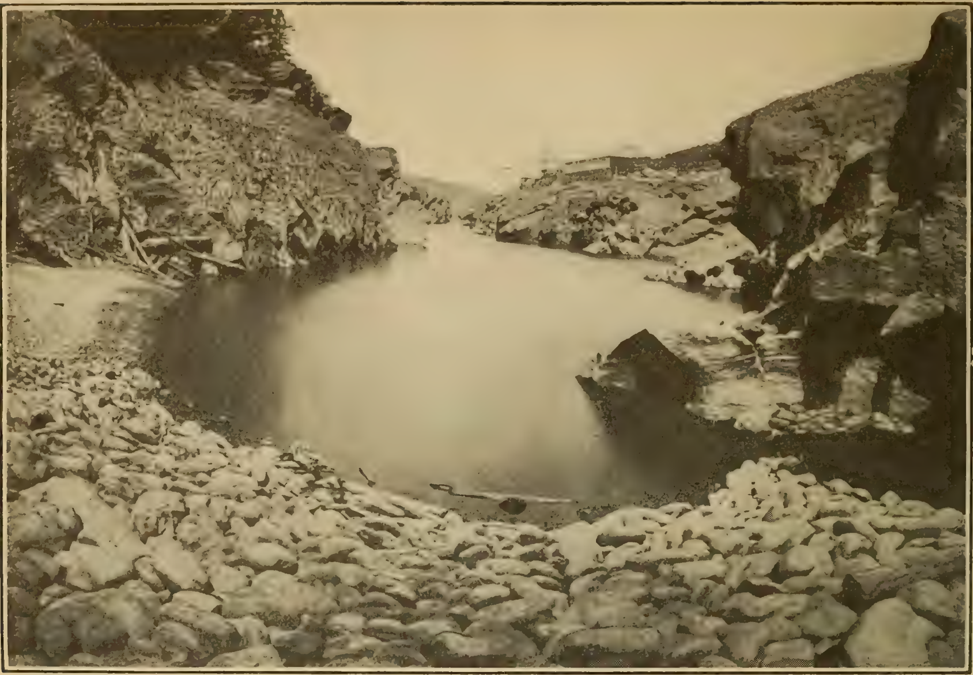


FIGURE 1.—DOWNSTREAM END OF "DEEP," SHOWING NUMEROUS VERTICAL POT HOLES ON SIDE WALL (LEFT)

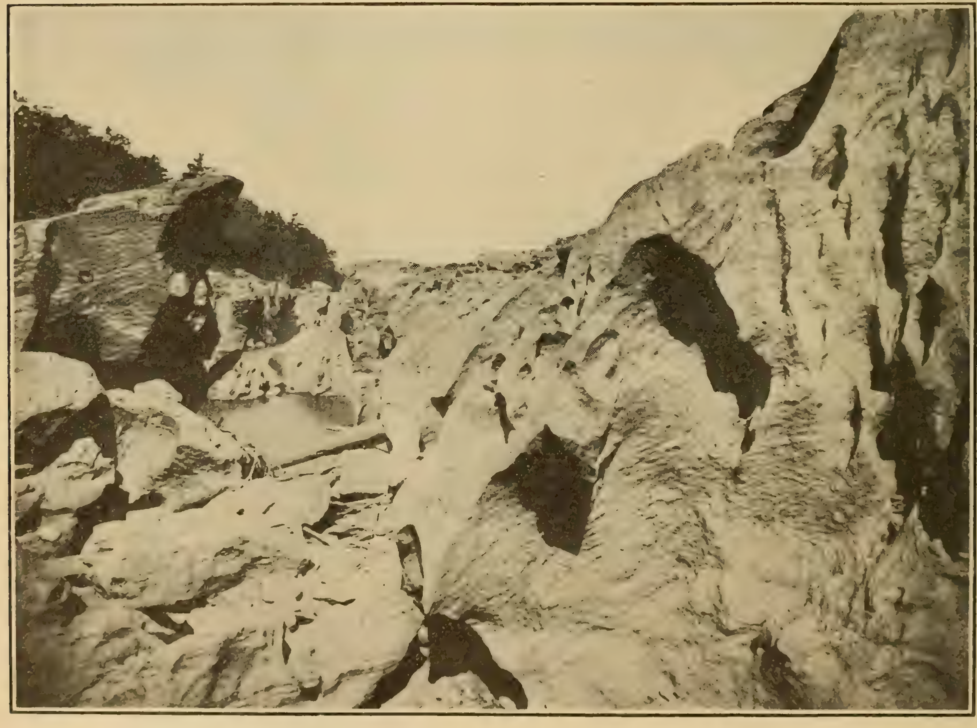


FIGURE 2.—VIEW SHOWING GREAT IRREGULARITY IN DETAIL OF GORGE EROSION

DETAILS SHOWING MANNER OF EROSION IN "DEEP" AT HOLTWOOD, PENNSYLVANIA

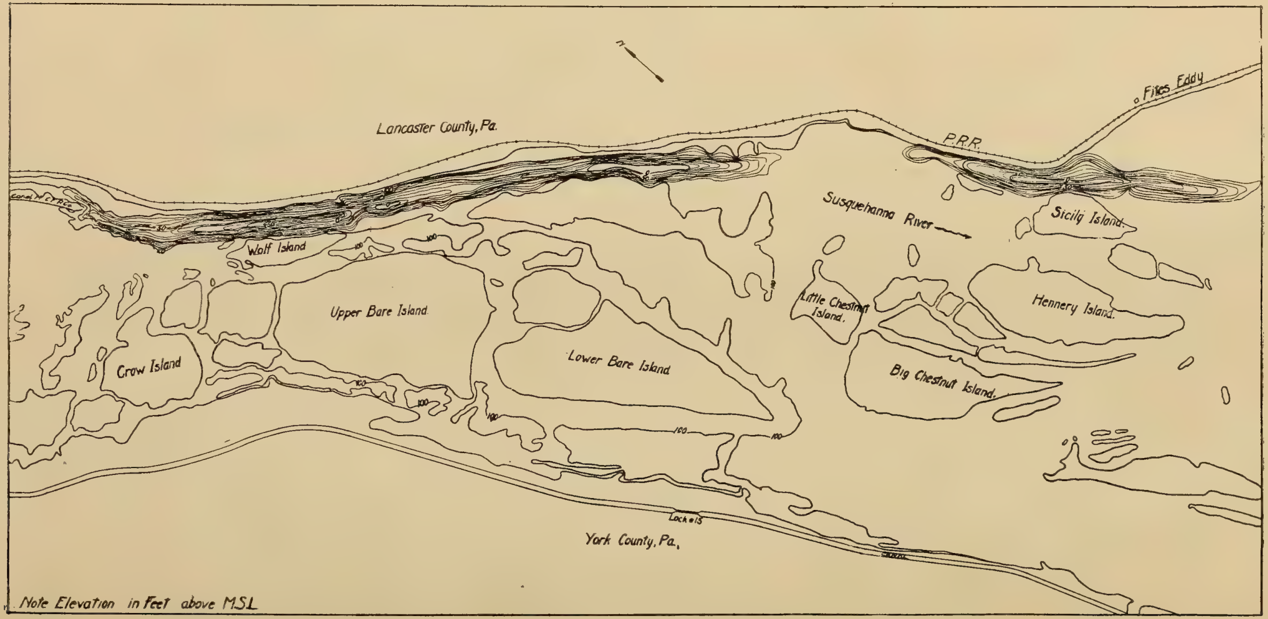

Lancaster County, Pa.
P.R.R.
Fites Eddy
Susquehanna River
Sicily Island.
Wolf Island
Upper Bare Island
Lower Bare Island
Little Chestnut Island.
Hennery Island.
Big Chestnut Island.
Crow Island
30
100
Lock 15
York County, Pa.
Note Elevation in Feet above MSL

FIGURE 6.—*Map of "Deeps" below Cullys Falls and above Fites Eddy, Pennsylvania*

Scale: 1 inch = 1,200 feet

undercutting of softer strata overlain by more resistant, as at Niagara.

The petrographic features are monotonously uniform along the river banks, giving no suggestion of differences in the resistance of adjoining units similar to those found in *subsequent* waterfalls, although the gorge as a whole may be considered a water gap. The undisturbed graded plain of the valley floor on all sides precludes the assumption of local warping.

The strike of the schistosity and major jointing are across the course of the river, which in turn shows little or no regard for the minor structures.

The only suggested condition remaining is that of a "narrows" produced either by local, as opposed to stratigraphic, variations in the hardness of the rocks or by temporary increases in the volume of the river. In such "narrows" it is conceivable that the increased velocity due to local reduction of the cross-section might increase and localize the erosive action of the river. Moreover, the local emponding of the waters upstream may have increased the water gradient enough to give a small but increasing downward, rather than lateral, erosion. In this way it is possible to explain the catenary form of the bottom profile, the

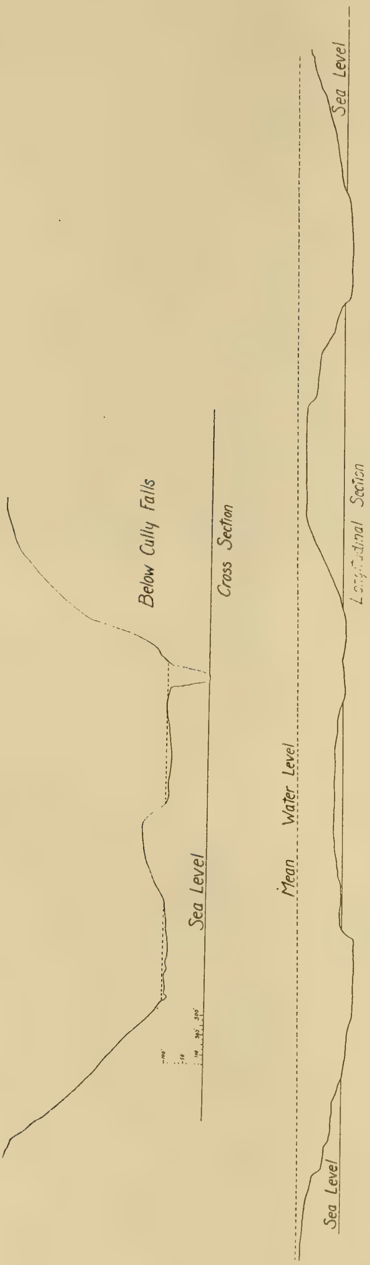


FIGURE 7.—*Profiles of "Deep" below Cullys Falls, Holtwood, Pennsylvania*

Scale: Horizontal, 1 inch = 2,000 feet; vertical, 1 inch = 500 feet

abundant small, nearly vertical pot-holes, and the sharp-edged rims in the flat valley floor.

Age of "Deeps"

Since the "deeps" have been cut in the incipient Susquehanna peneplain an attempt has been made to correlate them, by means of the peneplains, with other incidents in geologic history. When Davis[2] described the Somerville peneplain and Campbell[3] the Harrisburg, the topographic sheets covering the region between Harrisburg and the Chesapeake were lacking. The last of these, the McCalls Ferry sheet, was published in 1912 and is now available. A study of these later sheets from Harrisburg to tide enables one to trace the previously recognized peneplains downstream and to correlate them more or less closely with the Coastal Plain deposits of Maryland. The Harrisburg, which was regarded by Campbell as early Tertiary, corresponds to the Lafayette or Brandywine, now regarded as late Pliocene or early Pleistocene; the Somerville to the Sunderland; the Susquehanna in its two levels (one usually above and the other below water level) to the Wicomico and Talbot, or, with equal probability, to two phases of the Talbot. If this suggested correlation is confirmed by later study, then the cutting of these "deeps" must be post-Talbot in age and continue well into the Recent period.

Conclusion

The later history of the gorge may be sketched as follows:

Since Tertiary time the region has been part of the southeasterly sloping Atlantic plain, largely reduced to a grade of approximately 5 feet to the mile. During the intervening period the land has been gradually rising through a series of asymmetric oscillations until it is now perhaps 500 feet above its former level. This elevation has been spasmodic, with periods of quiet when the sea, the master streams, and side streams have more or less completely reduced their confines to grade and formed the well known Harrisburg, Somerville, and intermediate and later imperfect peneplains. It was during or just subsequent to the latest halt—thought to be more or less analogous to the Talbot terrace of Maryland—that the Susquehanna, by increased volume or constricted channel, developed six or more "narrows" in which the erosive action of the river was sufficiently increased to cut long, narrow, spoon-profiled "deeps." Their peculiarity lies in their extreme ratio of length to breadth, their depth of cutting (at times below present sealevel), and their bottom profiles, which rise downstream to the general valley floor and do not persist as canyons.

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[2] W. M. Davis: Boston Soc. Nat. Hist., Proc., vol. 24, 1889, p. 392.

[3] M. R. Campbell: Bull. Geol. Soc. Am., vol. 14, 1903, pp. 277-296.

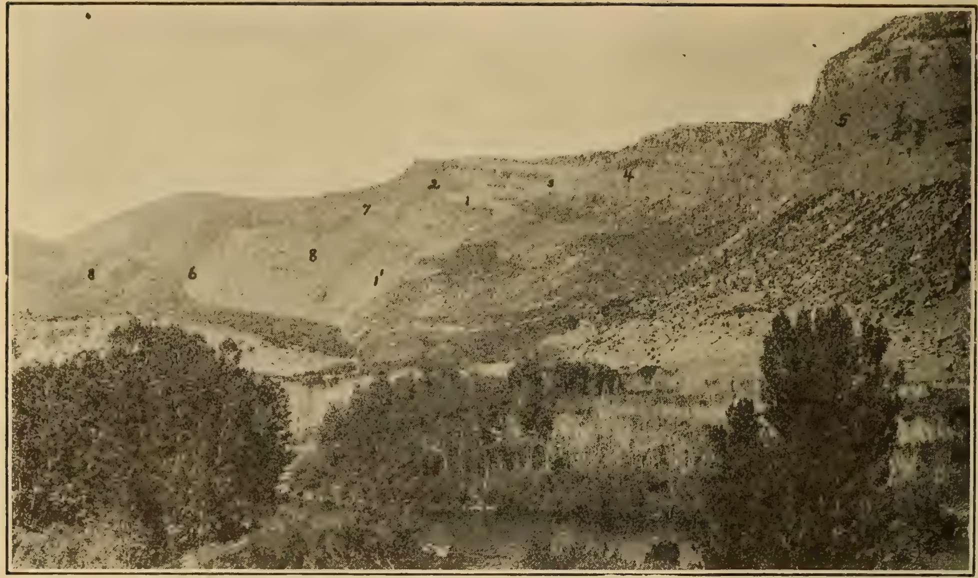

FIGURE 1.—GENERAL VIEW OF NORTH SIDE OF BULL LAKE CREEK CANYON AND ROCK SLIDE

1, rock slide; 2, Bull Lake Creek shales; 3, Shoshoni formation; 4, Bighorn limestone; 5, Madison limestone; 6, canyon in granite; 7, Deadwood sandstone; 8, granite. Photograph by Gillson

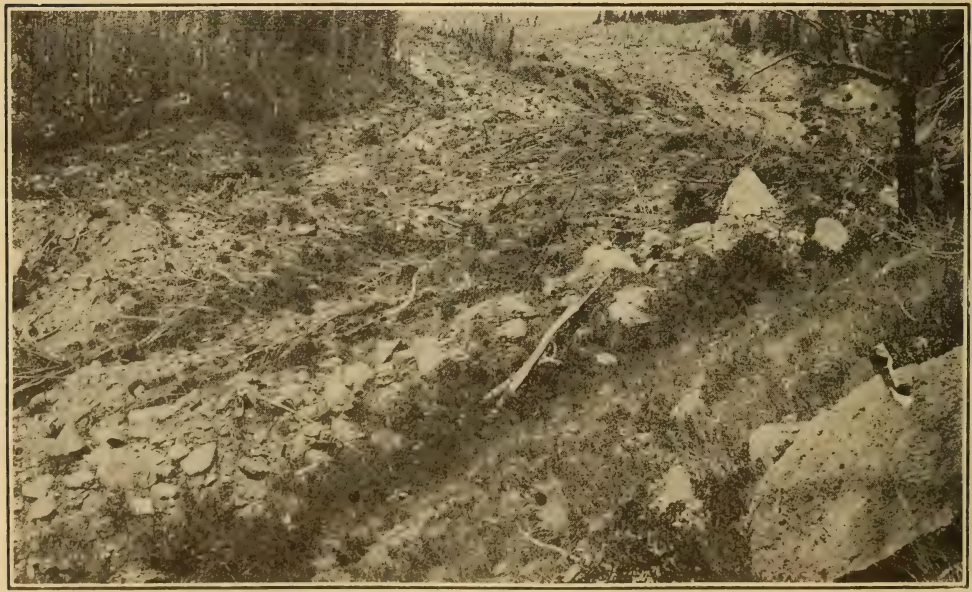

FIGURE 2.—DETAIL OF THE BULL LAKE CREEK SLIDE

The location of the photograph is between numerals 1 and 3, in figure 1. Photograph by Gillson

BULL LAKE CREEK SLIDE, WYOMING

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 28, PP. 347-350, PL. 21 JUNE 11, 1917

BULL LAKE CREEK ROCK SLIDE IN THE WIND RIVER MOUNTAINS OF WYOMING[1]

(*Read before the Society December 29, 1916*)

BY E. B. BRANSON

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Regional Relations

Bull Lake Creek is a swift stream tributary to Bull Lake, in Fremont County, Wyoming. For a stretch of from 7 to 12 miles west of the lake it occupies a canyon 2,000 to 4,000 feet deep with walls developed at two levels. The inner canyon is cut in granite to a depth of 2,000 feet. The walls of the outer canyon, separated from the rim of the granite gorge by a steeply sloping terrace 1 to 2 miles wide, rise to heights of 800 to 1,000 feet (plate 21, figure 1). The total width of the outer canyon is 3 to 4 miles at its western end, but decreases to about 1½ miles at a point 7 miles farther east. The walls of the outer canyon are composed of sedimentary rocks, which range from Cambrian to Pennsylvanian in age. At its west end the Bull Lake[2] Creek (Cambrian), Shoshoni (Cambrian), and Bighorn (Ordovician) formations make up the 1,000-foot cliff. The beds forming the cliff dip eastward at about 17 degrees, and almost opposite 3, plate 21, figure 1, the Madison limestone (Mississippian) comes in above the Bighorn and forms the top of the cliff, while the Bull Lake Creek formation drops out at the bottom. Eastward the Amsden (Mississippian), 76 feet thick, comes in above the Madison, forming a terrace, and finally the Tensleep (Pennsylvanian) adds a 400 to 600 foot cliff above the Amsden.

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[1] Manuscript received by the Secretary of the Society February 12, 1917.

[2] Formation names used by the writer in a paper in preparation.

DESCRIPTION OF THE BULL LAKE CREEK SLIDE

On the broad, steeply sloping terrace extending from the base of the northern wall of the outer canyon to the rim of the inner gorge is a rock slide, or rock glacier, about 5 miles long and one-half to one mile wide. Starting at the west end of the north cliff the rock slide moves down a 10-degree slope along the cliff base for 4 or 5 miles, then turns almost at right angles, crosses a terrace less than a mile in width, and enters the granite gorge.

The slide is made up of rock fragments varying from mud particles to blocks of limestone 40 feet in diameter, and the large and small fragments are mixed together in endless variety. The largest blocks are of Bighorn dolomite, but the greater part of the debris comes from the Shoshoni limestone. A series of longitudinal ridges traverses most of the slide and these are interrupted by many cross-ridges. Ridges made of fine material sometimes have one side 20 feet high, with a slope of 40 to 50 degrees. Cross-ridges covered with very large blocks of rock have separated, leaving deep valleys between, with black, shaly mud exposed at the bottom. On the sides there are ridges resembling the lateral moraines of glaciers and at the upper end an amphitheater-like depression resembles a cirque.

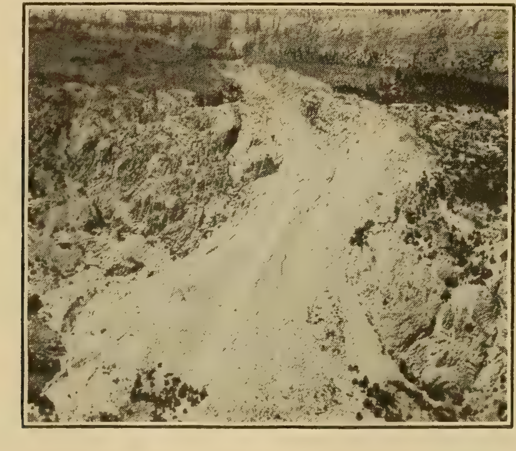

FIGURE 1.—*Lower End of Bull Lake Creek Slide*

Photograph was taken near numeral 1′, plate 21, figure 1, by Warner

The slide is covered with vegetation in various stages of destruction. On longitudinal ridges small aspens seem undisturbed, but in most areas the only plants that seem normal are small shrubs. Dead trees up to two feet in diameter are twisted, broken, uprooted, entangled.

Rate of Movement of the Slide

The lower end moves into the inner gorge of Bull Lake Creek, a stream about 60 feet wide and very swift, and the stream is able to handle all of the material brought in. A fairly well beaten path leads to the lower edge from the foot of the mountain, but movement has prevented the forming of a path on the slide itself. The writer has talked with only one man, besides those in his own parties, who has ever seen the slide, and no direct observations of movement have been made. In company with Prof. L. G. Westgate, the writer first visited it in August, 1913. Photographs made in 1913, when compared with those made in 1916, show material differences in the surface in various parts, but give no basis for estimating the rate of movement. The above are the only data available for estimating the rate of movement, but it must be slow and relatively constant.

Origin of the Slide

At the place of origin of the slide the cliff on the north side is made up of about 800 feet of limestone which rests on a shaly formation (Bull Lake Creek beds) 300 to 400 feet thick. The shale is very slippery, its crushing strength is small, and it appears that, unsupported on one side, it is unable to uphold the weight of the overlying rock and slides outward, causing great masses of the cliff to topple over. This falls on the shales below and accumulates to such depth as to cause movement in the wet, slippery shales which rest on the Deadwood sandstone or on other slippery shales. At the place where the Bull Lake Creek shales no longer form the bottom of the cliff the slide turns almost at right angles and moves away from the cliff.

Snow lies on the upper end of the slide until early in July; the underlying Deadwood sandstone furnishes water to it all summer, and small springs emerge on the surface in the dryest seasons, causing the shales to be slippery during the entire year.

Evidence that a vast amount of slumping occurs along the vertical cliff, and that the cliff is kept vertical by the slumping and movement of the slide, is furnished by the character of the valley. Bull Lake Creek flows in a granite canyon 2,000 feet deep nearly two miles from the cliff, and the creek has not been near the cliff since it began cutting into granite. A normal erosion history would have given a large talus slope at the base of the cliff and the cliff would have been reduced to slopes during the time necessary for excavating the inner canyon, but there is little or no talus at the base of the cliff next the slide. The valley has been glaciated, but the glacier seems not to have approached the north cliff near enough to interfere with the slide or to have disturbed talus if it had been present. East of the slide talus has accumulated to half the height of the cliff, although the stream is much nearer than it is in the slide region. The evidence seems to prove that the rock slide has removed the great masses of rock that slumped off, while the cliff retreated more than half a mile.

Other Slides in the Wind River Mountains

Rock slides occur on a small scale in several deep valleys in the Wind River Mountains, but they are high and far back in the mountains and have escaped observation. Blackwelder[3] mentions the "general absence of earthflows from such ranges as the Wind River Mountains," but in a later paper he says:

> "In a few cirques, talus glaciers, such as those described by Cross and Howe in the San Juan Mountains of Colorado, have been formed. On the northeast side of Sheep Mountains, at the northwest end of the Wind River Range, there is a good example showing the tongue-like form and surface corrugations."[4]

On the north side of Big Popo Agie River, 12 miles from Lander, Wyoming, a slide of large size was once active, but seems to have been quiet for more than 20 years, as a road built across it more than 20 years ago has not been disturbed. On the south side of the same stream a cliff about one mile long has developed by slumping, caused by the movement of the slippery Bull Lake Creek shales. On the south side of Little Popo Agie River, about 21 miles from Lander and opposite the mouth of North Fork, there is a slide similar to the one on the south side of Big Popo Agie. In all of the examples mentioned the active agent of movement is the Bull Lake Creek shale.

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[3] Bull. Geol. Soc. Am., vol. 23, p. 491.

[4] Jour. of Geol., vol. 23, 1915, pp. 334-335.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 28, PP. 351-374 JUNE 11, 1917

OROGRAPHIC ORIGIN OF ANCIENT LAKE BONNEVILLE[1]

BY CHARLES R. KEYES

(*Presented before the Society December 29, 1916*)

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[1] Manuscript received by the Secretary of the Society January 17, 1917.

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INTRODUCTORY

In a recent inquiry into the derivation of certain desert features of the Great basin, Great Salt Lake, and especially its precursor, the vaster Lake Bonneville, presented some seemingly anomalies which from a perusal of the literature alone could not be readily adjusted to the modern genetic scheme of physiographical development. This circumstance eventually led to several visits to the Utah field and a critical examination on the ground of the published data relating to the geologic history of the old desert lake. Concerning the origin of Lake Bonneville so many incongruities were found as to compel the abandonment of the prevailing hypothesis. Instead of a genesis due to conditions of moister climate induced by a Glacial epoch, the facts gathered seem to point not only to a pre-Glacial date of the lake's birth, but to a diastrophic rather than a climatic cause for its existence.

That the origin of the great Quaternary expanse of interior waters known as Lake Bonneville, of which the present Great Salt Lake of Utah is an all but extinguished remnant, may not be entirely climatic in character, as advanced by Prof. G. K. Gilbert,[2] is not a new thought. The possibility of the ancient lake's derivation through means of orographic movement was incidentally suggested by Prof. W. M. Davis[3] so long ago as 1883 in a summary review of Gilbert's preliminary account of his Bonneville investigations.[4] I am not aware that this suggestion has ever been pursued further. Its consideration now is the result of accidental rather than of premeditative causes. The recent observations indicate that this view not only has much merit in it, but that it has, unexpectedly, an unusual amount of critically supporting evidence that has never been even hinted at in the various discussions on lake subjects. Approach from a direction entirely different from anything previously attempted is mainly responsible for the present return to the theme.

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[2] Mon. U. S. Geol. Survey, vol. i, 1892.

[3] Science, vol. i, 1883, p. 570.

[4] Second Ann. Rept. U. S. Geol. Survey, 1881, p. 169.

The conclusion reached is that the great body of water of which Great Salt Lake is a last vestige is not, after all, an anomaly among desert features, but that it merely represents a special phase of a through-flowing stream that was not quite large enough to master the orogenic barrier which chanced to arise athwart its path, while its nearest neighbor and parallel stream, the Green River, reenforced by the Grand and other eastern tributaries, was sufficiently powerful to hold its own against all vicissitudes and to carve through the rapidly bulging Colorado dome a Titan among chasms. Blocked by such a formidable rampart, the old river spread out far and wide over the adjoining intermont plains, until finally, after its headwaters were diverted, it could no longer furnish the lake with its chief supplies.

INCONGRUITIES OF PREVAILING HYPOTHESIS

GENERAL STATEMENT

Viewed from a strictly lacustrine angle, ancient Lake Bonneville is surely an anomaly. Its consideration has been invariably a treatment of a typical moist climate phenomenon, with exact counterparts in such bodies of water as Lakes Erie and Michigan. Indeed, it is expressly stated in the Bonneville monograph that the latter's main purpose is to depict the features of normal lakes. How far this central concept has warped the interpretations of the features presented and has colored the historical account of the lake is difficult to estimate.

As a special phase of an exotic desert feature, Lake Bonneville's existence assumes a new meaning.

When in the course of a recent search through the literature relating to ancient Lake Bonneville for facts elucidating another theme various conclusions were met with which did not seem to be supported sufficiently by the testimony presented and statements were noted which were far from being satisfactory explanations of the phenomena displayed, it was found that only by actual examination on the ground could their verity really be substantiated. When later these evidences came to be critically passed in review in the field the incongruity of many of them was still further magnified. At the same time many additional facts were noted rendering necessary different interpretations of old records and the introduction of new ones.

UNUSUAL POSITION OF LAKE'S INTAKE AND OUTLET

Bear River, which is considered by some writers as the main tributary of old Lake Bonneville, supplying, it has been estimated, more than one-half of the total inflow, has an unusual course. It first flows nearly north, then turns sharply back on itself and runs almost due south. On leaving the mountains its canyon immediately opens out into a broad transverse intermont plain known as Cache Valley, which was at the time of its greatest expansion a long arm of the lake. On either side of the canyon's mouth the highest lake terraces are well displayed. Cache Valley also leads into the Red Rock Pass, which Gilbert is confident was once occupied by the lake's outlet to the Snake River of Idaho. The two locations are thus only a few miles apart. Accordingly, the inflow and outflow take place at practically the same point. Both are at the lowest spot in the lake's rim. Under such conditions the formation of any lake would be almost an impossibility except through means of especial pre-lacustrine circumstances, of which there has been as yet no suggestion.

PRECLUSION OF REGIONAL OSCILLATORY CHANGES

It is passing strange that in the very birthplace of that most brilliant of geologic concepts—the fault-block hypothesis of Basin Range structure, whereby the mountain prisms are fancied as tilting and floating as do ice-cakes in a river at time of spring break-up—the probability and even possibility of orogenic movement should be so completely overlooked when the chief Bonneville Lake problems came up for consideration and solution. There are in the region abundant evidences of recent diastrophic oscillations. Some of these disturbances were manifestly very considerable and took place in quite late geologic times. The lake terraces themselves plainly show notable warping. On the west side of the Great basin the Inyo earthquake, which occurred within the memory of men yet living, was accompanied by displacements of over 30 feet. A warping of less than 200 feet would direct the present headwaters of Snake River from the Bonneville basin, if they ever formed a part of that drainage system. On the other hand, an uprising of 1,000 or 1,200 feet at the south would effectually bar the waters of the lake at the time of its greatest expansion from reaching the Colorado River. The actual uprising of this tract, as indicated by the depth of the inner gorge of the Grand Canyon in this vicinity, is more than twice this figure. Such facts go to show in no unmistakable way that no consideration of the origin of Lake Bonneville is complete without critical determination of the values of the diastrophic factors.

INATTENTION TO PRE-LACUSTRINE CONDITIONS

The history of Lake Bonneville really does not begin with the lake as such at all. It goes back far beyond the time when the empounded waters were already gathered in greatest expanse. From whatever angle the theme is viewed, the pre-lacustrine features have a fundamental function in shaping all later events, for the genesis of the lake is not nearly so simple a process as to include only a mere filling of a chance depression with abundant waters from postulated glacier-fed streams. Perhaps the most important periods of the lake's history are the prenatal ones.

Omitting to take into account these prenatal lake conditions necessarily leads to a misunderstanding of some features, a wrong interpretation of many others, and concerning still others the introduction of unnecessary and irrelevant hypotheses. Inattention in this respect also develops unexpected incongruities and renders inexplicable otherwise easily comprehended characters.

COMPARISON WITH RELATED EVENTS OF NEIGHBORING DISTRICTS

With the numerous physical events which are known to have abounded in the region, the geological dates of which are now pretty well fixed, it is quite singular that those directly associated with the Glacial epoch should have been considered to the exclusion of all others. Even the connection of the lake with ice effects is not at all convincing, and later observations indicate that this is only partially pertinent. It is even possible that the existence, much less the birth, of Lake Bonneville was not only not associated in any way with the inferred consequences of a glacial climate imposed on the region, but that it really antedated by a very considerable lapse of time the dawn of the Glacial epoch.

Critical consideration of the later gorge-cutting of the Grand Canyon of the Colorado River, the canyon work of the Green River in the Uinta Range, the development of the Snake River drainage, the remarkable terrace work in adjoining areas, the spread of lava flows, and the minor diastrophic changes in the region is bound to throw a new flood of light on Bonneville affairs. The climatic factor may be finally found to be practically negligible.

INADEQUACY OF EXISTING DRAINAGE SYSTEMS

It was the manifest incompetency of the present drainage to keep up a great lake that caused the Bonneville historians to cast about for a water supply ample enough to satisfy all requirements. The simplest method was to postulate a larger supply from existing streams. Only by direct appeal to different physical conditions giving a moister climate could this be done. The Glacial epoch was thought to be near enough to fulfill the desired requirements. The step to glacial environment was short and easy.

The utter insufficiency of Bear River, the principal tributary of Great

Salt Lake, which furnishes more than one-half of the total supply to that body of water, necessarily demanded a much greater volume of water to feed the older and vaster lake. Bear River, however, does not display any marked signs of ever having been a much more pretentious stream than at present. There are reasons for believing that it may have been actually smaller formerly than now. The rest of the Wasatch drainage is notoriously inconsequential. With only the present drainage systems considered, it might be seriously questioned whether glaciation was ever very effective over the region or whether glaciers ever materially augmented the old lake waters.

PECULIARITIES OF SO-CALLED RED ROCK OUTLET

The present elevation of Red Rock Pass, the lowest point in the rim of the Bonneville basin, at the head of Cache Valley, is, according to Gilbert, about 370 feet below the highest shoreline level and about 30 feet above the Provo level. The north and south valley of which it is the high point is notably broad, the plain lying between the piedmonts of the Port Neuf Range on the east and the Bannock Mountains on the west being 10 to 12 miles wide. The two small brooks which have their rise in the pass and which run in opposite directions have cut only narrow, shallow channels in this plain. The bottom of the valley is covered by alluvial materials of no great depth. These wash materials are mainly coarse gravels which were evidently being transported southward when they came to final rest. Nowhere are there signs of the existence of an old gorge, such as would have been formed by a large river emptying a great lake. If such a canyon ever existed it is now completely obliterated. Farther north, near Pocatello, Idaho, the only trace of an old gorge is that filled with basaltic lava that plainly flowed southward toward Great Salt Lake. In fact, all the usual characteristics of a large outlet are singularly wanting.

The peculiar physiognomy of the Red Rock Pass district admits of an interpretation very different from that which a generation ago was so plausibly advanced.

CONSPICUOUS ABSENCE OF MOIST CLIMATE FEATURES

One of the noteworthy characteristics of the Bonneville basin is that the only details of relief expression which commonly distinguish moist-climate lands are discernible on the east side of the great depression where the shore was the mountain base. The small streams coming down from the range seem to be doing about the same work now that they did ages ago. Along the entire western side of the basin no trace of stream-work is visible. Catchment basins there are large. After all his discussion, Gilbert himself is compelled to admit that

> "If the rainfall in Bonneville times was very great, as compared with the modern, these catchment districts should have furnished tributary streams; and such streams flowing over tracts of alluvium, the accumulation of ages, should have transported large quantities of it to the margin of the lake and constructed deltas of it. We seem thus to have an intimation that the climatic change, whatever its nature, did not affect the rainfall in a degree commensurate with the difference in area of lake surface."[5]

NON-COINCIDENCE OF LAKE AND GLACIAL EPOCHS

Since Gilbert's Bonneville studies were made, so many new facts about the region have been recorded that no longer does appeal have to be confined to a period of glaciation in order to find an adequate explanation for the gathering of waters of a great desert lake. In fact, in point of time the formation of the lake and the advance of the continental ice-sheet do not now appear to be exactly contemporaneous. The lake seems to have been well along toward complete desiccation before the Glacial epoch set in. Glacial causes may have affected the level of the lake in some of its later stages, but certainly not in its earlier ones. The notion of dependence of lake on glacial climate is obviously a forced conclusion.

INFELICITOUS COMPARISON OF LAKE'S OUTLET WITH NIAGARA

The attempt to establish an analogy between Lake Bonneville and Lake Erie and between the Niagara River and the Red Rock Pass outlet is, as it now appears, a fatal objection to the prevailing hypothesis of origin of the desert lake. Nowhere in the Red Rock Valley is there the slightest trace of an old gorge, the formation of which is not so remote but that there would have remained conspicuous walls several hundred feet high. Gilbert regards the old hypothetical outlet as possibly larger than the Niagara River and capable of draining the lake in 25 years.[6] This rate necessitates the assumption of an extensive and hitherto unknown rapidity of cutting back of the Red Rock Pass falls and an excavation of at least 400 feet in depth before the lake would cease to overflow its rim.

Under these circumstances, it is strange that the lake apparently continued to lower its level with the same speed after the supposed outlet no longer remained such as it did before. No doubt the Niagara coloring is much too deep for desert conditions.

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[5] Mon. U. S. Geol. Survey, vol. i, 1890, p. 167.

[6] Mon. U. S. Geol. Survey, vol. i, 1890, p. 176.

Pre-lacustrine Relief of Bonneville Region

EARLY QUATERNARY DRAINAGE

In his inductive picture of the geographic cycle developing under conditions of arid climate, Prof. W. M. Davis depicts the withering away of the old prevailing lines of drainage and the conversion of all stream valleys into waterless desert plains. In the main this transformation is regarded as taking place so early in the cycle that only under rare circumstances would any vestiges of the ancient stream features be preserved. If ever trace were left of this early stage, it appears that in the long Great Salt Lake basin there might be one.

The broader features of the pre-arid drainage of the region lying between the central chain of the Rockies and the Sierra Nevada are not so very difficult to fancy. A few of the larger watercourses having extralimital heads survive all the viscissitudes of climate and diastrophism. In the cases of others all vestiges have long since disappeared. There are some of which shadowy traces might still persist.

Between the Rocky Mountains and the Wasatch Range the master-streams doubtless occupied much the same positions that the large through-flowing rivers do now. The Grand and the Green rivers were the main streams which, uniting to form the Colorado River, ran through to the sea. Under originally moister climatic conditions it would be expected that the Colorado River would receive at least one other large tributary—one from the west side of the Wasatch Ridge. Possibly still another large watercourse also helped to drain the extreme western parts of the Great basin.

ANCIENT VIRGEN MASTER-STREAM

The possibility of a large river having once occupied the succession of valleys on the west side of the Wasatch Range seems never before to have been carefully considered. The inductive reasoning conducted by Professor Davis in support of the idea of streams formerly traversing many of the long bolsons of the arid regions is yet so new that its necessary consequences have not yet been widely tested in the field.

In most deserts the especial forces of aridity have acted so long and so vigorously that all traces of any former stream systems, if they ever existed there, have long since disappeared. In the instance of a possible master-stream on the west side of the Wasatch Mountains the conditions are peculiarly favorable to the detection of some direct testimony bearing on its former presence. Moreover, there is the Green-Colorado River to aid in determining what features to expect. The latter stream is remarkable in that it has been able to maintain itself in spite of the fact that three great mountain barriers have successively arisen across its course. The means by which it has been able to do this is also a clue to the reasons why other streams of the region were not permitted to accomplish the same thing. The former existence of such a stream in Bonneville basin is borne out by many facts.

A large river occupying the Bonneville Valley before the lake period naturally would be the twin stream of the Green River. Its main gathering basin, like that of its sister stream, would be most likely in the Rockies of the Yellowstone Park district. Its course would follow the deep and relative narrow valley between the Port Neuf and Bannock Ranges, enter the broader Bonneville basin, which it would traverse its entire length, and finally reach the Colorado River at the point where that stream makes its great sharp bend from a westward direction to a southern one. The recent visits to the region had for one of their main objects the gathering of facts bearing on the support or disproval of such a working hypothesis. With the former the observations seemed to agree.

HEADWATERS OF OLD VIRGEN RIVER

The complex of head streams which now gather together to make up the Snake River of Idaho presents strong evidences of being a newly adjusted system. Traces of relatively recent diversion are indicated in many places. One of the principal tributaries, the Port Neuf River, after flowing directly south for many miles, swings sharply around to the northwest and empties into the Snake River near Pocatello town. Another stream, the Bear River, likewise turns sharply on itself, its upper half running parallel to the lower half, but in a diametrically opposite direction. Other streams of the region have equally erratic courses.

Near Pocatello the Port Neuf Creek crosses an old stream channel of large size which is now filled high by lava, for the ancient drainage-ways and valleys of southern Idaho seem to have often flowed with liquid rock as well as water. This old channel extends apparently far to the northward. Southward it enters Red Rock Pass and coincides with the old river bed which Gilbert interpreted to represent the outlet of Lake Bonneville. That this old channel belonged to a south-flowing and not a north-running river of considerable size seems clearly indicated by disposition of the old stream gravels. The pebbles composing these gravels are not chiefly derived from local rock ledges, but from Precambrian crystallines, such as characterize the Yellowstone Park region. They are numerous, of nearly uniform measurement, and of a size that suggests their removal a distance of about one hundred miles from their parent ledges.

The amount of crustal warping necessary to turn the entire system of head streams of the present Snake River into Great Salt Lake basin is hardly more than 200 feet. The choking of the main channel by lava or the damming by slight orogenic movement could easily have directed the headwaters of such a stream out on to the Idaho lava plains. Both Gilbert[7] and Gannett show that by changes of 100 feet the waters of Bear River also might be turned into the Snake River, or those of the Blackfoot and Port Neuf rivers might flow into Great Salt Lake basin. In the valleys of these last mentioned streams comparatively recent basalt flows have produced notable alterations in the drainage.

GENERAL ABSENCE OF TRIBUTARIES

It is not at all probable that between its mouth and the juncture of its principal headwater streams the old Virgen River had any larger or more lateral feeders than the inconsequential tributaries which now come in from the Wasatch Mountains. During the later lake period the small importance of these side streams is directly measurable by the size of the deltas which were formed in the still waters. From the west there was no augmentation in the river's volume.

At the present time Gilbert estimates the capacity of these tributaries at one-half the volume of Bear River. If it is assumed that in the prelacustrine epoch the Snake River poured its waters at Pocatello into the Virgen channel, these tributaries supplied less than one-fortieth or one-fiftieth of the total volume of the old river.

LOWER REACH OF OLD VIRGEN WATERWAY

One of the most surprising drainage features of the Colorado Plateau region is the canyon of Muddy Creek, which in southeastern Nevada joins the present diminutive Virgen River a few miles from the point where the latter unites with the Colorado River. Muddy Canyon is large out of all proportion to the insignificant brook which now occupies its wide, flat-bottomed floor. For a distance of 50 miles from Caliente Station, where the San Pedro, Los Angeles and Salt Lake Railway enters it, the bottom of this canyon is about 2,000 feet above sealevel. Before it unites with the Virgen Canyon it suddenly drops to a level about 400 feet above the sea. The trough thus opens into the Colorado trench far up near the summit of the inner canyon wall. To all intents and purposes the Muddy and Virgen troughs are what in glaciated regions would be termed hanging valleys. Dutton[8] likewise calls attention to similar features connected with other large waterless tributaries of the Grand Canyon region.

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[7] Mon. U. S. Geol. Survey, vol. i, 1890, p. 219.

[8] Mon. U. S. Geol. Survey, vol. ii, 1882, p. 227.

The Muddy-Virgen Canyon could only have been excavated by a stream at least as large as the Snake River of Idaho or the Green River before it unites with the Grand River. It seems impossible for such a diminutive waterway as that now flowing in the canyon to have accomplished such an amazing amount of work.

TYPICAL THROUGH-FLOWING STREAM OF DESERT

If before the lake period the long Bonneville Valley was occupied by a river the waters of which flowed through to the sea, there is added to this small and special group of streamways another example. Starting as a considerable stream fully as large as the present Green River is in the Uintas, probably it received along its course little or no augmentation to its waters and entered the Colorado River through a long, deep canyon. Doubtless, also, it was larger when it entered the Bonneville Valley than when it left it. In all respects it was a typical through-flowing stream of the desert, heading extralimitally and taking no part in the relief development of the country through which it passed. Although smaller than any of them, it was a fit companion of the Rio Colorado, the Rio Grande, the Rio Pecos, and the Nile River.

This old Virgen River stands for a distinct stage in the natural course of elimination of all waterways through gradually increasing aridity. Had it been somewhat larger it could have readily overcome the orogenic barrier which began to arise across its path, and had its extralimital headwaters not been diverted it would have remained today a typical large desert stream flowing through to the ocean. Had it failed to surmount its growing southern barrier and had its headwaters not been cut off, Lake Bonneville in its fullest development would doubtless have persisted to the present time instead of only its shallow last remnant that we call Great Salt Lake; but unusual viscissitudes defeated all its efforts to remain a through-flowing river. Depedalization, corporal inflation, and decapitation are unusual misfortunes for rivers to undergo. They fall to the lot of very few streams. Possibly the old Virgen River is the sole representative of its kind.

RECENCY OF SNAKE RIVER CHANNEL

The most striking feature connected with Snake River is the general absence throughout its course in southern Idaho of any marked valley. It flows over the lava plains in a channel that is often without appreciable banks. Whenever it has begun to corrade a noticeable trench the latter has merely sunk straight down a short distance, with no bottom lands bordering and no valley on either side, sloping gradually down to the water's edge. Only along its lower reach, before it debouches into the Columbia River, does it become notably canyon-cutting. This fact is as remarkable as it is unexpected. From any commanding point the prospect which spreads out before the eye leaves the impression that the Snake River was somewhere toward its headwaters suddenly turned out of its original course on to the illimitable lava plain and there picked a way that was the lowest line. Surely this stream can not have worked very long in its present position. With the volume of water which it carries, with a high gradient of 8 feet to the mile, and with an elevation of 4,500 feet above sealevel in southeastern Idaho, it should, if it really were an old river, have its channel sunk deep in the ground in a canyon that in grandeur would be second only to the Grand Canyon of the Colorado in Arizona. Farther north, in central Washington, the Columbia River, when it was dammed by an ice-tongue in late Glacial times, cut the deep canyon of the Grand Coulée, 100 miles long, through solid basalt.

The edges of lava flows which cross the course of the Snake River at several points where they produce falls do not seem to have been sufficiently extensive to act as dams to prevent the river's normal cutting effect. These falls appear rather to attest the extreme recency of the date at which the stream was directed over its present course.

Orographic Movement in Bonneville Area

RECENT DIASTROPHIC CHANGES

Although in the Great basin the effects of mountain-making movements are wide-spread and extensive, they mainly date to a more remote period than has been generally assumed. Except in a few places, late diastrophic change nowhere appears to impart to the region its dominant relief expression. Nevertheless in the Bonneville basin recent diastrophic activity is quite appreciable. It is measurable by the differences in elevation of the ancient shoreline at different points. The plane of the old water level is a warped surface, with an incremental value between extremes of nearly 400 feet, or about the distance between the Bonneville and Provo terraces.

Over the western half of the basin the present differences in elevation of the old lake surface is barely 25 feet. In the other half of the basin there is a pronounced eastward tilting of nearly 200 feet. Thus is shifted the present Great Salt Lake against the base of the Wasatch Range, whereas otherwise the remnantal body of water would be occupying the Great Salt Desert 50 miles to the southwest.

The main argument for the existence of an outlet for Lake Bonneville at the Red Rock Pass north of Cache Bay is based on present elevations. Analysis of the measurable diastrophic movements that have taken place since the highest stage of water really precludes all possibility of the lake's ever having overflowed its rim. The later Bonneville terraces have not been observed nearer than 10 or 12 miles of the head of the postulated outlet. Above this point the projected level of highest water lies 355 feet. Of this interval about 100 feet are taken up by the depressive warping. Another 125 to 150 feet, which represents probably not one-half the actual displacement value, is taken up by measurable faulting of very recent date. A diastrophic oscillation of 200 to 250 feet more than suffices for all the manifold drainage changes of the region as far north as Yellowstone Park.

LATEST UPRISING OF COLORADO DOME

In the course of his historical account of the Grand Canyon, Dutton makes much of the revived regional elevation in late Tertiary or early Quaternary times. The magnitude of this movement is indicated in the cutting of the inner gorge of the canyon. It is estimated to be between 3,000 and 4,000 feet in the central part of the broad dome, gradually diminishing outwardly in all directions to nothing. That the effects of this crustal uprising reached well into the Bonneville basin is clearly shown by the fact that even the highest shorelines at the extreme south are sharply warped; so that, as has been already mentioned, a difference in elevation within a distance of a few miles is more than 300 feet. The amount of pre-lacustrine movement in the vicinity must have been even greater. It is quite possible that a part of the warping, especially in the south, is to be accredited to Wasatch diastrophism; or it is more than likely that the pre-lacustrine movement belongs entirely to the Colorado Dome disturbance, and that the post-lacustrine movement is to be ascribed chiefly to Wasatch orogeny. This possible deviation is a matter of mere detail and does not vitally affect the main issue. At any rate the uprising of the Colorado dome was sufficiently effective at this distance from its center to form the southern barrier of the lake basin at the time of the water's greatest expansion and highest stage, when its level was nearly 1,000 feet above that of the present Great Salt Lake.

If there once were a through-flowing river traversing the ancient Bonneville Valley, the local uprising must have been rapid enough to outdo the most vigorous corrading powers of that stream. Finally, a point was reached when the watercourse ceased to reach the Colorado River and its waters became impounded behind the barrier formed. Dutton places particular emphasis on the rapidity of the latest uprising of the dome, and later observers fully substantiate him.

HIGH CHANNEL OF VIRGEN-MUDDY RIVER

The elevation of the bottom of the canyon occupied by Muddy Creek nearly 1,500 feet above the water level of the Colorado River proclaims the speed with which the Colorado dome has recently revived its upward movement. Muddy Canyon was excavated manifestly by a very much larger stream than the one now occupying it. This feature appears to also characterize other tributaries of the Colorado River. In view of the fact that a generation ago the glacial activities were so widely evoked to explain everything geological, it is not so very strange that Dutton should also ascribe this peculiarity to conditions of moister climate when the present diminutive and often intermittent creeks were hypothetically considerable rivers. That some of these rivers might have been deprived of their waters by the effects of the uprising movement itself without notable change in the local climate does not seem to have occurred to him. Under these circumstances, it is quite remarkable that any traces of the ancient drainage system should survive the vicissitudes of mountain-forming, lake, and desert wind activities. This is especially true since the latter have come to be better understood and their tremendous potency recognized. There would now remain no wind-gap at the southern end of the old valley. The canyon of the one-time stream draining the basin in the pre-lacustrine epoch might be preserved beyond the line of the orographic barrier; but wind erosion and eolic deposition would soon obliterate all traces of the old channel at and on the flanks of the barrier.

The pertinent questions which now arise are whether or not the present size of the Virgen-Muddy Canyon is commensurate with the probable volume of the old stream, and whether it was possible for such a stream once to have crossed the line of the orographic barrier? To both of these questions the answer is strongly affirmative.

DIVERSION OF HEADWATERS OF OLD VIRGEN RIVER

Every explanation of the genesis of Lake Bonneville necessarily postulates a much larger supply of water than that at present afforded to Great Salt Lake. In accordance with the prevailing hypothesis, this surplus volume of water was secured through means of moister climatic conditions that were superinduced by the Glacial epoch. With the passing away of the latter, according to the same notion, the great expanse of waters rapidly diminished.

Ordinary lakes have their size and height of surface controlled by their outlets. Lakes without outlets, and especially bodies of water standing in dry regions, have both of these factors made a function of the rate of evaporation, which is always high. It is probable that in the case of Lake Bonneville the prism of water present at any particular time is capable of mathematical calculation. When the inflow was at its maximum, the waters, owing to the peculiarities of the local relief, spread out over the adjacent plains until an area was attained the evaporative coefficient of which exactly balanced at any particular moment that of the intake. With so high an evaporative value as 80 to 100 inches a year and with so vast an area of shallow waters, the fluctuations of the lake level must have been relatively rapid and numerous.

That Lake Bonneville was fed by streams other than those now tributary to Great Salt Lake, and that the headwaters of the pre-lacustrine Virgen River drained into the basin and indeed formed and mainly supported the old lake, is evidenced by many facts. When, however, the principal feeder was diverted, the lake waters soon fell in consequence 1,000 feet.

To just what extent the diversion of the headwaters of the Old Virgen River was due to diastrophic movements and what to volcanic disturbances is now difficult to estimate. The last mentioned cause is probably the determining one; but the first-named one by itself appears to be perfectly competent to accomplish the results.

MAGNITUDE OF NECESSARY MOVEMENTS

In the north the diversion of the Snake River headwaters back and forth between its present channel and the basin of Great Salt Lake may be readily accounted for by a differential movement of less than 250 feet.

In the south the amount of movement necessary effectually to barricade the old watercourse is considerably greater. It was at least 1,200 feet, as shown by the elevation of the highest shore terraces. In reality it was somewhat more than this figure.

Altogether the necessary crustal oscillation is so surprisingly small as to be almost beyond expectation.

Volcanic Disturbances affecting Lake Conditions

CHOKING OF MAIN TRIBUTARIES BY LAVA FLOWS

The volcanic phenomena in and about Bonneville basin are both numerous and extensive. The principal expression of the more recent activities of this kind are the basaltic streams. In point of time these extend backward from almost the first settlement of the region to far beyond the remotest lacustrine stage. As is also well shown in other parts of the Great basin, river channels sometimes flowed with water, sometimes with molten rock almost as mobile.

On the assumption that Lake Bonneville was formed in an ancient river valley by the unsurmountable uprising of the Colorado dome across the path of the stream while the headwater tributaries continued to pour into the basin their supplies with unchecked volume, the query comes up whether there is not reason other than the climatic one which may fully account for the disappearance of the great lake. In view of the more recent better understanding of the workings of desert agencies of erosion, it may be asked if it is really at all necessary to postulate the lowering of Bonneville waters after the manner of Lake Erie by the cutting back of the Niagara gorge.

All available evidence recently obtained indicates in no uncertain manner that the insignificant channel extending from Red Rock Pass to beyond Pocatello and now occupied by Marsh and Port Neuf creeks is not the remnant of an old outlet of the lake, but one very recently formed. The old channel which appears to be the course of the main tributary of the lake instead of the outlet is not one of the magnitude of the Niagara River, but of a considerably smaller stream. At and immediately south of Pocatello the old channel is filled to overflowing with basalt—two flows in fact. At one point the present Port Neuf Creek which is flowing southward abruptly turns westward, crosses the lava stream in a narrow gorge a couple of hundred yards wide, and continues back northward along the flank of the lava-filled channel. The slight northward slope of the present lower Port Neuf Valley is not necessarily proof that this has long been the direction of local moving waters. The lavas manifestly flowed in a southern direction, and presumably the river before them did also, until it was directed out on to the Idaho plains by the choking of its youthful course by the basalt flood.

The behavior of the Port Neuf River is by no means unique. It has its counterpart in other parts of the arid region. The Rio Mora of New Mexico once experienced a lava flood.[9] The Maxwell ash cone, situated five or six miles distant from the river, breached its crater wall and let loose a basalt stream four miles wide. This lava stream flowed over the surrounding plain a distance of over 30 miles before it reached the brink of the Mora Canyon, there nearly 1,000 feet deep. This it filled for a distance of many miles to a depth of 400 feet, forcing the river to cut a new canyon in the soft strata alongside of the basalt mass.

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[9] Proc. Iowa Acad. Sci., vol. xvii, 1911, p. 165.

FORMATION OF SNAKE RIVER

Reasons for believing Snake River to be a very modern stream are presented in another connection. If the lava which filled the gorge running east of Pocatello represents the channel of a south-flowing master-stream, into which once gathered all the headwater branches of the Snake River, the incursion of molten rock in such bulk as is plainly manifested at once effectually blocked all further southward movement of the waters of these head streams both through this channel and its valley. By way of contrast the Rio Mora, when, owing to the great depth of its canyon, the lava was unable to completely fill it, excavated a new channel alongside of the old one. That the voluminous waters of the Snake River when turned out suddenly on to the arid Idaho plains should form a notable river rather than a lake is due to a number of peculiar circumstances. Possibly at first ephemeral lakes were formed which, as their low rims were successively pierced by overflow waters, were quickly drained, and only a stream persisted. Various lava flows may have determined the dams for the impounded waters. Today the locations of these dams may be indicated by the positions of the different "falls" which characterize the course of this river.

By all expectation the Snake River should be a typical example of an antecedent stream. In arid regions, however, as Davis well observes,[10] antecedent rivers persisting from a previous cycle against the deformations by which the new cycle is introduced must be rare, because such rivers should be large, and large rivers are here unusual. In so far as the course of the stream under consideration is determined by the slopes of its new surface, the Snake River is a consequent stream; but not in the usual sense of the term, for general deformation does not enter into the problem at all. This great waterway really belongs to a new class by itself.

Among streams generally the Snake River presents a rather unique genesis. It is now essentially a typically through-flowing stream of the desert, with extralimital headwaters. Without taking any part in the general sculpturing of the landscape of the region through which it passes, it is a river seemingly out of place. It is not a stream which merely lengthens or shortens with the oscillation of the ocean's strandline. It is not a stream that is formed of several streams united end to end. It is not dependent for its existence on the run-off of storm waters from the surface of a warping area. It is not a stream that has held its own from a former cycle. It appears to have burst full grown from its old course out on its new surface, finally to discharge into the Columbia River through the valley of one of the latter's minor tributaries which it greatly and rapidly enlarged. It is clearly imposed on the country it traverses. It is an imposed river.

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[10] Journal of Geology, vol. xiii, 1895, p. 382.

CONTEMPORANEITY OF NEIGHBORING PHYSICAL EVENTS

TERTIARY STRATA IN BONNEVILLE BASIN

As yet the subject of geological age of the formations represented in the Bonneville region has not been critically investigated, nor has it received the careful attention that it merits. In near-by districts Mid Tertiary beds are known to be widely distributed. Under the title of Neocene, Gilbert[11] notes that in places these formations extend over the rim of the lake basin and are independent of the old shorelines. Although this fact severely limits the remoteness of the lake epoch, it does not necessarily support the assumption of its contemporaneity with the Glacial epoch. Between Mid Tertiary and Mid Quaternary, or Pleistocene, the time is long. It permits an antiquity of the lake that is not usually considered.

INNER GORGE OF GRAND CANYON

Two notable epochs of uprising mark the uplifting of the Colorado dome. During the earlier one of these the larger streams managed to maintain their original courses. In the later epoch, when the present inner gorge of the canyon was chiefly formed, the progress appears to have been so rapid that some streams were not able to cut channels apace with the upward movement. The commencement of the inner gorge Dutton[12] is inclined to place in Mid Tertiary times.

It is manifest that if the regional uplifting produced a barrier which any of the through-flowing streams could not conquer, the river waters would soon become dammed and a lake would result. The beginnings of Lake Bonneville must have thus soon found expression in late Tertiary times probably.

SIMILARITY OF OLD LAKE TERRACES

Of the several shore terraces which Lake Bonneville displays those of the Provo stage, about 600 feet above the present level of Great Salt Lake and 350 feet below the highest stage of the impounded waters, are the most conspicuous and best preserved. Compared with the Provo terraces, the highest Bonneville terraces are poorly preserved. Over considerable stretches of the old shoreline the terraces are now completely effaced.

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[11] Mon. U. S. Geol. Survey, vol. i, 1890, p. 214.

[12] Mon. U. S. Geol. Survey, vol. ii, 1885, p. 227.

Although the epochs of the Bonneville and pre-Bonneville terraces have been correlated with the two assumed parts of the Glacial period, there appears to have been never any critical evidence adduced in support of the notion. Instead of the Glacial epoch being possibly bipartite, as it was everywhere attempted to be proved when the Bonneville monograph was written, it has since been found to be even more complex and to have had half a dozen distinct stages or advancements of the continental ice-sheet. Under these circumstances the interpretation of the Bonneville facts observed is not so satisfactory as it might otherwise be.

There chance to be, not so very far away from the Great Salt Lake, localities where lake terrace and glacial phenomena are directly associated. The Okanogan Valley, in central Washington, is a glacier-worn trough. Three hundred feet above the river level is a conspicuous continuous terrace which marks a shoreline of a lake when the Columbia River was blocked to the south by a great ice-tongue extending out of the valley of the present Chelan Lake. Now the Okanogan terraces are about as well preserved as those of the Provo stage in the Bonneville basin. Since their appearance the physical surroundings, the character of the formation, and the climatic conditions of the two localities have been to all intents and purposes the same, it may be assumed that they were formed about at the same time. The Provo stage probably comes within the last quarter of Lake Bonneville's existence. Hence, according to this test, only the Provo stage is to be brought within the limits of the Glacial epoch.

DEPAUPERATION OF MOLLUSCAN SHELLS

In his reference of the genesis of Lake Bonneville directly to glacial causes, Gilbert lays great, if not chief, stress on supposed dwarfing of certain molluscan shells found in the lake deposits. This line of argument is based mainly on R. E. Call's conclusions concerning a comparison of the lake shells with the same forms now living. These conclusions are highly misleading and seem to be really a warping of the facts to fit a theory. Call's similar conclusions regarding the loess mollusks of the Mississippi Valley[13] are of like character and were, moreover, drawn when it was universally thought that the loess was a strictly glacial deposit. As conclusively demonstrated recently by Prof. B. Shimek,[14] Call's results, in so far as Iowa is concerned at least, are entirely erroneous and his conclusions wholly unwarranted. So their bearing on

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[13] Am. Jour. Sci. (3), vol. xxiv, 1882, p. 202.

[14] Bull. Lab. Nat. Hist., Iowa State Univ., vol. v, 1901, p. 195.

Bonneville climate is not at all strengthening. An entirely new examination of the data would doubtless lead to wholly different conclusions.

GLACIAL HYPOTHESIS OF LAKE'S ORIGIN

At the time when the climatic explanation of lake genesis was advanced, no other hypothesis seemed available. Indeed, the possible duality of the Glacial epoch was then receiving wide attention. The fact that in arid regions an entirely different set of erosional agencies come into play that are fundamentally distinct from those which are most active under conditions of moist climate had not been suspected. In the attempt to make a great lake in a desert land a necessary consequence of the near-by presence of a continental ice-advancement, a strong bias existed and an erroneous interpretation of facts resulted. Nowhere in all the elaborate discussion that took place on the subject was there any direct or critical evidence adduced to show that the time of the greatest expansion of Lake Bonneville coincided with that of the farthest southward advance of the northern ice-sheet. In light of the recent observations demonstrating that this could not be, all the arguments formerly presented in support of this contention prove notably weak.

So much stress has been put on the direct association of glaciation with the Great Basin lakes that the competency of the common cause now demands definite evaluation. Most considerations are qualitative only. Since the recent careful mapping of the glaciers of the Uinta and Wasatch Mountains by Prof. W. W. Atwood[15] quantitative calculations are now possible. The most conspicuous feature thus brought out is their insignificance. So inconsequential must have been their influence on lake conditions that one almost wonders why the two were ever genetically associated at all. Singularly, too, the very points of contact, the meeting of lake shore and moraine, where the critical testimony would be expected to be adduced, are the most inconclusive of all.

An important climatic feature which in mountainous arid lands seems to be quite generally overlooked is the notable change in humidity that takes place with elevation. The higher parts of the loftier mountains enjoy moist, temperate conditions in the midst of the dry, torrid conditions of the surrounding desert. Often when the latter has an annual rainfall of only 5 to 10 inches the precipitation on the mountain tops rises to as high as 30 inches and more, or about the same that prevails in the upper Mississippi Valley. Under conditions such as these glaciation might well be initiated on the high points without appreciably affecting the moisture content over the lowland plains. When, further, it is remembered that a lowering of only three degrees in the present mean annual temperature would induce glacial conditions in the Scottish Highlands, and that a similar reduction of 12 degrees in the upper Mississippi Valley would cover that region with the same great continental ice-sheet that characterized it in Kansan times, it is readily inferred that the production of the relatively insignificant glaciers on the Wasatch and Uinta Mountains would not require necessarily a very marked change of temperature nor a notable increase in regional humidity over that now existing.

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[15] U. S. Geol. Survey, Professional Paper No. 61, 1909.

Expressions of Arid erosive Influences

MASTERY OF DESERT EROSIONAL AGENCIES

In late years our notions concerning land sculpture in arid tracts have undergone great change. Throughout such regions the conditions which obtain under normal moist climate no longer prevail. Wholly different processes attain ascendency. Phenomena of the desert which once were seemingly hopelessly inexplicable now genetically resolve themselves into their developmental stages. Recognition of the tremendous potency of the winds as an erosional power under conditions of excessively dry climate puts a new aspect on the derivation of all landscape features of the arid lands. Recent discussions on these phases of the subject need not, however, be reiterated here.

DESTRUCTION OF ANCIENT LAKE TERRACES

The occurrence of the old lake terraces on the flanks of the Wasatch Mountains which constituted the eastern shore of the lake, and on protected sides of other mountains, gives rise to much speculation as to the cause of this peculiarity in their distribution. At first Gilbert thought that he had found an adequate explanation by attributing the phenomenon to prevailing westerly winds. Later the same author was inclined to the view that there was close sympathy between the magnitude of the shore features and the fetch of the efficient waves, and that the greater the distance through which waves travel to reach a given coast the greater the work accomplished by them. This generally recognized principle only partly explains the local situation. The strictly desert influences are not taken into account; and, after all, the question is not really answered. The question of the preservation of the terraces in some places to the present time remains untouched as ever.

By all principles of known desert corrasion the terraces of Lake Bonneville should have been long since completely obliterated by the action of winds and wind-driven sands. Situations of two kinds appear to have escaped—those on the lee side of the main body of water and those on the lee side of islands or mountains. The maximum abrading action of winds in dry countries is near the level of the general plains surface. The terraces on the east shore were protected from this action by the waters of the lake itself. On the northern and eastern flanks of the mountain isles, like the Oquirrh Range, the lake terraces retain their freshness longer than elsewhere because of the fact that the prevailing winds could not reach them.

On the west shore of the old lake, where the waters were shallow, whatever terraces there were were necessarily quickly destroyed either by being removed by wind-action or by being overwhelmed by drifting sands from the adjoining deserts.

PLANORASION BY WINDS

In descriptions of Bonneville basin the smooth intermont plains are repeatedly accounted for by regarding them as old lake bottoms. The evidence is at first glance so seemingly obvious that the idea has been extended to cover all of the flat valleys of the Great basin as well as other parts of the arid regions. In desert tracts the notably plains-forming tendency of wind-action appears to be its most characteristic result. For a large proportion of the arid intermont plains the lacustrine hypothesis has now to be given up. It is highly probable, also, that even on the plains over which once stood the waters of the lake the surface has by the late action of winds been made smoother than when the waters originally covered the areas.

DERIVATION OF LAKE SEDIMENTS

It is commonly assumed that the lake sediments which are displayed in considerable thickness throughout the Bonneville basin are mainly derived from the fine materials held in suspension by the waters of the tributaries entering the lake. Recently closer examination indicates that these lake beds are not composed of clay, but of materials of much coarser texture—particles like those of loess or adobe. This being the case, the inference is that the materials making up the beds are chiefly merely the adobe soils blown into the lake from the neighboring deserts. This view is also supported by other classes of evidence.

ROCK-FLOORS OF DESERT PLAINS

The Bonneville basin is one of the few desert plains which is probably more or less deeply filled with soil materials. Although most intermont plains of the arid regions appear to be areas of profound degradation and to have well defined rock-floors only scantily covered by soil, the valley under consideration seems to be an exception. The lake sediments are of especial interest because of the fact that they are mainly neither clays nor sands, but materials of intermediate-sized grain. Instead of being brought in by streams, these materials were originally doubtless dusts that settled on the surface of the lake waters. The persistent body of water was the only tract where wind-blown soils could come to rest within the limits of the arid land. The area presents a marked contrast to the Mojave plains to the southward, where the upturned strata are conspicuously beveled, the resulting surface being a typical rock-floor which in many spots is swept clear of soil.

Recapitulation

Summing up the salient features of the foreging record of recent observations on the conditions surrounding the genesis of a great body of water in a desert region, it appears that

(1) The presence of such a lake as ancient Lake Bonneville is not necessarily dependent on notably moister climate than at present;

(2) The existence of the lake is genetically associated with the recent and extensive uprising of the Colorado dome;

(3) The Red Rock Pass marks the location of the main tributary rather than the outlet of the old lake;

(4) The lake probably never had an outlet, the disposition of its augmented waters being entirely accounted for by the high evaporation and the ready lateral expansion of its borders;

(5) The Bonneville Lake occupied an old but little disguised river basin, across the lower end of which developed an orographic barrier that the ancient stream was unable to corrade apace, the lake thus formed representing an orographically dammed river valley;

(6) The beginning of the lake epoch long antedated the Glacial epoch, even the time of greatest expansion being long prior to the commencement of Glacial time;

(7) The extensive modifications of the ancient river's headwaters have occurred immediately before, during, and subsequent to the Glacial epoch;

(8) The pre-lacustrine river suffered both depedalization and decapitation;

(9) The lake's history prior to the formation of the highest shorelines was probably much longer than the lapse of time since;

(10) Lake Bonneville is not an anomalous phenomenon among desert features, notwithstanding the fact that it possessed antithetical relations to its climatic surroundings. It is merely a special phase of a large through-flowing river that was yet not quite large enough to corrade even a narrow canyon through the mountainous barrier which chanced to rise athwart its path. With no outlet and undiminished augmentation to its volume, a lake was formed, the waters of which rose and spread until evaporation and inflow reached equilibrium. When later the chief tributary was diverted by lava flows, the level of the lake rapidly fell until equilibrium was again finally established with the inflow of the remaining tributaries, as is seen in the present Great Salt Lake.

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METAMORPHISM AND ITS PHASES[1]

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INTRODUCTION

Science is the coordination of fact with fact, fact with principle, and principle with principle. It depends on the rigorous use of words. Neither fact nor principle nor coordination can rise into full consciousness until phrased in unimpeachable terms. Unceasing attention to the use of words therefore represents a principal duty of every scientific investigator. Experience shows how hard it is, in a fluid science like geology, to hold technical words to constant, universally accepted definitions. The causes of this unrest are many: progress in the discovery of facts, progress in coordination, progress in interpretation or theory, and, one must add, the varying subjectivity, if not carelessness, of writers.

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[1] Manuscript received by the Secretary of the Society December 27, 1916.

Few geological topics are as far-reaching and profoundly important as rock metamorphism. Few have had, and are having, such increase of content, both empirical and theoretical. Invented eighty years ago, the words "metamorphic" and "metamorphism" are almost as old as scientific geology. Unnumbered facts and theoretical ideas have been clustered under these captions. How far have their original definitions borne the strain of new discoveries? What changes in their definition have been proposed since the issuing of the first edition of Lyell's "Principles of Geology"? Is any definition of metamorphism acceptable to the geological profession as a whole? To what extent should theoretical explanation enter into its definition and into that of each of its phases? Is a systematic classification of metamorphic processes possible? In view of much uncertainty as to conditions affecting the development of crystalline schists, is an attempt to form such a classification at the present time advisable?

These are the questions to be discussed in the following pages. The writer's form of statement has been made clearer as the result of debates with his colleagues, Professors Graton, Palache, and Warren, and especially because of analysis of the original manuscript by Mr. A. S. R. Wilson, candidate for the doctor's degree at Harvard University.

DEFINITION OF METAMORPHISM

FORMER USE OF THE TERM

Early in its history, though not at the beginning, "metamorphism" was used in two different senses, and corresponding definitions are still recognized by some authors. "Metamorphism in the broader meaning" approximates more nearly to the literal etymology, denoting simply rock alteration. "Metamorphism in the narrower meaning" has led to several definitions, all of which, however, disregard literal etymology and exclude rock weathering, or rock cementation, or concretionary action, or all of these examples of alteration, from the field of metamorphism.

The range of the definitions is illustrated in the ensuing historical sketch, which, brief as it is, suffices to show the need of a universal language in dealing with multitudes of facts and principles vital to geology.

HISTORY OF THE WORD "METAMORPHISM"

In the first edition of his "Principles of Geology" (1833, volume 3, page 374) Lyell introduced "metamorphic" to geology. Neither there nor in later editions does he appear to have used the noun "metamorphism," but he wrote of "metamorphic rocks" and the "metamorphic theory." The very invention of the Greek compound, identical in literal meaning with the familiar "transformed" or "transforming," shows from the start that Lyell did not intend his word to cover all rock alterations.

He later elaborated the theory of metamorphism, in his "Elements of Geology" (1838), stating (page 219): "Metamorphic . . . expresses a theoretical opinion that . . . strata, after having been deposited from water, acquired by the influence of heat and other causes a highly crystalline texture." On page 23 one reads: "It is true that all metamorphic strata must have been deposited originally at the surface, or on that part of the exterior of the globe which is covered by water; but, according to the views above set forth, they could never have acquired their crystalline texture unless they had been modified by plutonic agency under pressure in the depths of the earth." He continued (page 379): "The metamorphic rocks must be the oldest—that is to say, they must lie at the bottom of each series of superimposed strata—because the influence of the volcanic heat proceeds from below upwards."

From the sixth to the last edition, Lyell's "Principles" contained the following passage, giving a virtual definition of metamorphism: "The transmutation [of fossiliferous strata into such rocks as gneiss, mica schist, or marble] has been effected by the influence of subterranean heat acting under great pressure, and aided by thermal water or steam and other gases permeating the porous rocks, and giving rise to various chemical decompositions and new combinations" (sixth edition, 1840, London, volume 1, page 320).

Lyell early adopted the view that magmatic and connate gases and vapors, as well as mere heat, are important agencies in metamorphism ("Elements of Geology," 1838, page 246).

Durocher (1846, page 546) defined metamorphism as (translated) "the sum of the effects of transformation, of change of nature or texture, which the rocks composing the earth's crust have undergone." He pointed out that metamorphic rocks are most developed in regions affected by crustal deformation, though also habitually along igneous contacts. He laid great stress on the influence of heat in metamorphism, yet classified as metamorphic several types of change at ordinary temperatures, including oxidation and hydration of rocks by weathering, as well as concretionary action.

Virlet (d'Aoust)—1847, page 502—used the expression "métamorphisme normal" to signify the alteration of rocks by interior heat acting at a time when the earth's crust was comparatively thin; he assumed the alteration to have been aided by pressure, and especially by the presence of water, both magmatic and connate. Virlet described "normal metamorphism" as also "general." He held that primitive rocks as such can no longer be found at the surface of the globe, because they have all been metamorphosed since their original "refroidissement." As indicating his grasp of the importance of solvents in metamorphism, he wrote that, if original crust rocks were ever discovered, they must prove to be free from water. Three years before (1844, page 846) Virlet had emphasized the injection theory of gneiss, using the expression "roches d'imbibition," a formula for an essential idea in French thought on the problem of metamorphism, since the days of Boué and de Beaumont.

A formal definition by Studer (1847, page 116) shows how early the conflict began between the Lyellian conception of metamorphism and the formally logical use of the word in its literal meaning of "transformation." Translated, Studer's statement runs as follows: "Metamorphism in the broader sense [includes] all effects exercised on rocks through forces other than gravity and cohesion. Metamorphism in the narrower sense is confined to rock transformations which are produced, not through the influence of the atmosphere or of the water on the earth's surface, but, directly or indirectly, through activities which originate in the interior of the earth."

In his Lehrbuch der Geognosie, C. F. Naumann (1850, page 751) distinguished "normal or general metamorphism" from "abnormal or local metamorphism." Translated, his words are: "Normal metamorphism is the transformation of a rock through a quite general cause, which has affected the rock in its entire extension and represents a regular (gesetzmässigen) and necessary phase in the gradual development of the rock. Abnormal metamorphism is the transformation of a rock through extraordinary causes, a transformation which has affected the rock only in certain parts of its extent, without marking a necessary stage in the development of the rock."

Among the phases of normal metamorphism Naumann included the consolidation (cementation) of sand, pebbles, and mud—to form, respectively, sandstone, conglomerate, and argillite. He recognizes, however, that many of the transformations necessary in the development of a rock, such as cementation, and also the changes in rocks produced by volcanic exhalations, are not covered by "metamorphism in the narrower sense." Naumann stated that the use of the word in the narrower sense was customary in 1850. He specially emphasized the rise of the isogeotherms in geosynclinals as one important condition for normal metamorphism, but makes no mention of mountain-building in this connection.

According to Naumann, abnormal or local metamorphism is characterized by "evident" causes, in contrast to the more hidden or "latent" (von Morlot) causes of normal metamorphism. The chief "evident" causes he lists: (1) combustion, as in the case of changes in clays through the burning of a coal bed; (2) volcanic gases and vapors, as in the conversion of limestone into gypsum by exhaled hydrogen sulphide; (3) magmatic heat at igneous contacts, and (4) impregnation with water and hydrous solutions, as in the case of local dolomitization or silicification.

Delesse (1857, page 90) held that "metamorphism in its most general meaning" includes all alterations undergone by rocks. He made the distinction between normal or general metamorphism and abnormal or special metamorphism, the former being due to invisible causes, the latter being due to "accidental but visible" causes operating over small, separated areas. This dichotomous division carries the implication that, for practical purposes, Delesse really excluded weathering from the list of metamorphic processes.

Daubrée (1860, page 59) introduced the expression "métamorphisme régional" as an improvement on ("plus juste que") "métamorphisme normal" and as less vague than "métamorphisme général." He gave no formal definition of regional metamorphism. Though dwelling on the rôle of crustal deformation in the evolution of the Precambrian gneisses and schists, Daubrée argued energetically against strict uniformitarianism as applied to the genetic problem of the crystalline schists. He wrote (page 123): "The old gneisses testify to the high temperature of the earth's surface in ancient times."

In the present connection Lossen's writings are noteworthy for two reasons. He included lithifaction or consolidation (Festwerdung) of sediments among the metamorphic processes. He introduced (1875, page 970, or at an earlier date) the first technical name, "Dislocationsmetamorphismus," for the concept already described by Baur, Sharpe, Sorby, and others, and now generally called dynamo-metamorphism or dynamic metamorphism.

Von Hauer (1878, page 109) defined "metamorphism in the widest sense" as including "the sum of the changes which rocks undergo after their formation (Bildung), through the influence of heat, or chemical agents, or of both together, . . . the changes not going so far that the masses are completely destroyed (zerstört) and therewith cease to be rocks (Gebirgsarten)." In this sense he held that all rocks are metamorphic;

for example, the cementation of loose sand by the infiltration of calcium carbonate furnishes a metamorphic rock, and a somewhat hydrated lava is metamorphic. However, according to general usage, only those rocks are called metamorphic in which alteration has reached a higher degree and has taken the form of new crystallizations. He gave pseudomorphism as a type of metamorphism with this narrower definition. He treated diagenesis as a "Mittelweg" between metamorphism and original "Bildung." Weathering was excluded from the phases of metamorphism.

Phillips (1885, page 356 ff) described as metamorphic "all those parts of aqueous strata which have been transformed in structure or appearance by subterranean heat, or heat developed by pressure applied since their deposition." He recognized two kinds of metamorphism: *structural*, due to burial (pressure and heat) or to orogenic movement (as in the origination of cleavage), and *molecular*, not expressly defined, but illustrated by the conversion of "earthy" carbonate of lime into marble.

According to Prestwich (1886, page 397), "metamorphism is that molecular and structural change in the strata of the sedimentary series, or in the rocks of igneous origin, whereby they have undergone a transformation in the chemical combination of their elements, in mineral constituents, and in structure, so that their original condition has been more or less modified and altered and their characters disguised." He points out that this is in a sense true of all stratified rocks, since nearly all have been changed by cementation, segregation, infiltration, or pressure. He concluded that the term "metamorphism" should be restricted to "those greater chemical and mineral changes, caused by heat combined with pressure and moisture." Prestwich distinguished contact, regional, and normal metamorphism.

Regional metamorphism includes (1885, page 425, and 1886, page 408) "changes effected by the agency of the physical causes to which Mr. Mallet referred the fusion of the volcanic rocks, namely, *the heat produced locally within the crust of the earth by transformation into heat of the mechanical work of compression, or of crushing of portions of that crust.*" In the 1885 paper, page 425, he wrote: "Normal metamorphism I would confine to signify, as hitherto, the changes caused by the heat due to depth, on the supposition of the existence of a heated central nucleus of the earth." However (page 430), "normal metamorphism depends not so much on high temperature as on pressure and the presence of water." To its operation he attributed (1886, page 413) the larger and more common class of metamorphosed strata, the alteration of which has been due to a cause more general than igneous-rock heat (contact metamorphism) or orogenic-crush heat (regional metamorphism). This general cause is the internal heat of the earth, which becomes efficient only after burial.

Teall (1888, page 438) wrote of "metamorphism": "This word is usually restricted in geological literature to changes which a rock undergoes in mineralogical or chemical composition and internal structure through the operation of heat, heated water, or vapor, and mechanical agencies. It is either local or regional." He excludes (page 410) weathering and also the effects of "thermal waters, fumarole and solfataric action." He recognizes only contact and dynamic (called "regional" in the earlier part of his book) metamorphism.

Reyer (1888, page 554) made metamorphism include the disintegration of rocks through weathering; the mere cementation of loose material into coherent rocks; and the recrystallization of rock material in depth, giving pseudomorphism as an example.

Harker (1889) published a brief general discussion of the nature of metamorphism. Under that name he groups (page 15) "all processes which result in a partial or complete crystallization or recrystallization of solid masses of rocks." His "hydro-metamorphism" implies low pressure and low temperature and is illustrated in the deposition of interstitial quartz during the conversion of sandstone into quartzite—a common kind of cementation. Harker prefers "thermo-metamorphism" to "contact metamorphism," defining the former as alteration under conditions of low pressure and high temperature. Conditions of high pressure and high temperature lead to "dynamo-metamorphism," while those of high pressure and high temperature lead to "plutono-metamorphism." He states that dynamo-metamorphism implies "a *direct* correlation between mechanical and chemical energy." His classification is avowedly made "for rough purposes."

In his Traité de Géologie, de Lapparent (1893, page 584) defined metamorphism as including all changes "affecting rocks after their deposition"; and again (page 711) as "the sum of the chemical changes made after the deposition of sediments." In another passage (page 612) he expressly states that the alteration of rocks by the weather and by the penetration of surface waters is to be regarded as a metamorphic process. Yet throughout the long sections of his book that deal with weathering and the effects of percolating water the words "metamorphism" and "metamorphic" never appear. Instead, he uses "alteration" and "transformation." In practice, therefore, he found it unnecessary to use "metamorphism" according to either of his broad definitions.

Zirkel (1893, I, page 572) designated metamorphism as the phenomenon "that a given rock has, through a geological cause which is independent of the original formation (Bildung) of that rock, undergone such a change that a well characterized *new* rock *type* is developed." He excludes weathering from its list of phases.

Turning to J. D. Dana's Manual of Geology, one reads (1895, page 310): "Under metamorphism might be included the chemical changes in rocks and minerals that take place at ordinary temperature. But these run down into the common results of decay and are more conveniently kept separate." While thus excluding weathering, Dana thought that the cementation of sediments should be regarded as a phase of metamorphism. He distinguished local and regional metamorphism, the latter being (1) incipient, (2) crystallinic, (3) paramorphic, (4) metachemic, or (5) endo-crystallic. According to the source of the heat involved, he further distinguished "statical" and "dynamical" metamorphism. Statical metamorphism is (page 440) "that dependent on heat of a statical source—the earth's mass and the vapors about it." This kind characterized the "Lithic Era" in the globe's history, the long period before the ocean condensed on the original crust. In this matter Dana was evidently not a uniformitarian.

His Archeozoic æon was (page 441) characterized by dynamical metamorphism, which is "dependent on heat from a dynamical source—that is, heat generated by movements in the thickening crust." On the other hand, he notes (page 322) that "the earth's internal heat has always been a contributor to the heat of the earth's crust, and much more so formerly than now, and would, therefore, have supplemented largely the heat generated by friction." From a passage on the same page of the Manual one must infer that Dana regarded "dynamical metamorphism" and "regional metamorphism" as rigorous synonyms.

In the last edition of his Textbook of Geology, A. Geikie (1903, page 424) defines metamorphism of rocks as "rearrangement of their constituent minerals, and most frequently the production of a new crystalline structure." A fuller statement is given on page 764: "Mere alteration by decay is not what geologists denote by metamorphism. The term has been, indeed, much too loosely employed; but it is now generally used to express a change in the mineralogical and chemical composition and in the internal structure of rocks, either locally, by intruded masses of highly heated material, or regionally, through the operation of mechanical movements, combined with the influence of heat and heated water or vapor." However, Geikie does regard mere "induration" of discrete materials as a metamorphic process.

Geikie adopted the dichotomous division into contact metamorphism and regional metamorphism. He recognizes deep burial as one of the causes of metamorphism, but decides (page 805) that the "statical phase" of regional metamorphism is "not so striking in results as dynamical metamorphism."

According to Van Hise (1904, page 32), metamorphism "means any change in the constitution of any rock." He therefore includes all weathering processes; all other changes produced by vadose waters; the cementation of sediments or pyroclastic rocks; as well as rock changes due to heightened pressure or temperature, or both. Basing his work on the theses that (page 40) "the only workable classification of metamorphism is geological," and that (page 43) depth is "the most important of the influences which determine the character of the alterations of rocks," Van Hise considers these in terms of his zones of katamorphism and anamorphism.[2]

Chamberlin and Salisbury (1906, volume 1, pages 426 and 432) apply the term "metamorphism" to the "more profound changes" in rocks, the "more profound changes of induration and composition . . . essentially reconstruction." They exclude both weathering and mere cementation from the list of metamorphic processes, though pointing out that metamorphism is often "but an extension and intensification" of the change called induration or cementation. As usual in modern textbooks, dynamic action is emphasized; Chamberlin and Salisbury do not mention static or load metamorphism.

Haug (1907, pages 176-177, 185) does not give a formal definition, but states that high temperature, high pressure, and the presence of water are essential to true metamorphism. He apparently excludes from it hydration, oxidation, cementation, and decalcification. He divides metamorphic processes into two classes—"contact" and "general." Like Termier, he denies the power of dynamic metamorphism to do more than *mechanically* change a rock or to affect its mineralogical composition. Haug adopts Michel Lévy's view that contact metamorphism becomes confluent with "general" metamorphism as the depth increases.

In the last edition of his "Elemente der Gesteinslehre," Rosenbusch (1910, page 72) excluded weathering and decomposition in general from the list of metamorphic processes, though stating (page 578) that diagenesis is transitional into metamorphism. He defined diagenesis as comprising all changes in a sediment during and after its deposition until the stage of consolidation (Verfestigung) is reached; diagenesis may even include (page 485) certain changes induced by moderate deformation. Besides contact metamorphism, Rosenbusch admitted only dynamic metamorphism, which he named in 1886. For the latter Rosenbusch gave regional metamorphism, mechanical metamorphism, and dislocation metamorphism as synonyms. On page 73 is the following definition (in translation): "As dynamo-metamorphism we designate the sum of the changes in the mineralogical constitution and structure of a rock, due to the effect of orogenic processes. . . . We regard pressure as the operating factor in dynamo-metamorphism, without specifying whether pressure acts directly, as such, or indirectly, as, for example, through a rise of temperature." A further indication as to what he thought concerning the real nature of metamorphism as a whole, a passage on page 575 may be quoted, in translation: "The crystalline schists are eruptive or sedimentary rocks which have undergone geological transformation under the essential control of the geo-dynamic phenomenon ['Gebirgsdruck,' orogenic pressure]." Throughout his writings there appears to be no hint that load metamorphism need be considered.

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[2] When used geologically—that is, in reference to depth below the earth's surface—the "katamorphic" and "anamorphic" of Van Hise have respective meanings nearly opposite to the "katogen" and "anogen" of Becke (1892, page 297), or Kalkowsky (1886, page 29), or Haidinger (1850, page 301). See also B. Cotta's "Geologische Fragen," Freiberg, 1858, page 94, where the author formally adopts the latter pair of words, coined by Haidinger, to express a dichotomous division of all rock alterations. Leith and Mead (1915, page xix) have so redefined "katamorphism" and "anamorphism" that these processes are thereby to be considered as having no necessary relation to depth at all. Once again it is clear how the student of the future will be troubled by the flux of definition and usage.

Apparently Grubenmann excludes weathering and ordinary cementation from the field of metamorphism. However, he adds to the complexity of the problem by dividing (1910, page 45) rock transformations into three classes: *a*, metamorphism in the narrower sense; *b*, contact metamorphism; and *c*, metamorphism by magmatic injection and assimilation. Though he explains the crystalline schists as chiefly the product of mountain-building, he recommends (page 126) that the term "dynamo-metamorphism" be wholly given up, since it easily leads to the wrong notion that purely mechanical or pressure phenomena are implied. He actually suggests that the simple word "metamorphism" should be used in its place!

Scott (1911, pages 406 and 409) defines metamorphism as the "profound transformation of a rock from its original condition by means other than those of disintegration." He believes that the consolidation of sediments should be regarded as a phase of metamorphism, yet groups its processes in two classes only, under the captions contact metamorphism and regional *or* dynamic metamorphism.

Lindgren (1913, page 66 to 69) writes that metamorphism "has lately been employed in a wide sense, so as to cover any change in the composition and structure of a rock, through whatever agency and with or without gain or loss of substance. In this wide sense the term would include weathering and ordinary alteration of rocks at no great depth. This usage was adopted by Van Hise, but is not generally accepted, and the tendency seems to be to reserve the term for cases where the transformation of one rock to another is strongly marked, as in gneiss from granite or mica schist from clay shale. Though the mechanical effects of pressure may be conspicuous, metamorphism is always characterized by chemical changes in the component minerals; the composition of the rock itself may remain constant." He gives a definition of *weathering* as including "the changes of rocks near the surface due to the decomposing and oxidizing action of percolating waters above the permanent water level." The *zone of weathering* has a depth "determined by the level of the ground water or by the depth to which free oxygen can penetrate in large quantities."

Tornquist, in a recent textbook (1913, page 18), distinguishes as (*a*) "regionalmetamorph" those metamorphic rocks which have originated in their present form under a heavy rock cover; as (*b*) "kontaktmetamorph" those which owe their present character to the influence of igneous magma; and as (*c*) "dynamometamorph" those developed under orogenic pressure. The separation of (*a*) and (*c*) is worthy of note. Tornquist makes two astonishing suggestions. He proposes to call the change from clay to shale "Fossilisierung"; the change from shale to clay slate "Veränderung," and the change from clay slate to phyllite or mica schist "Metamorphose."

According to Boeke (1915, page 384), metamorphism represents the sum of the effects of high temperature, or high pressure, or both, so acting on a solid ("fertig gebildete") rock that its constituents are no longer in physico-chemical equilibrium. He admits three kinds: (*a*) dynamic metamorphism, with pressure playing the principal rôle; (*b*) thermometamorphism, with temperature in the principal rôle; and (*c*) contact metamorphism, which in his view implies the entrance of foreign substances, derived from invading magma, and further implies metasomatic interchange. Boeke makes no explicit statement as to the relative significance of either load or static metamorphism. He seems to exclude weathering and ordinary cementation from the domain of metamorphism.

Pirsson (1915, page 315) defines metamorphism as "a general term for all those changes by which the original characters of rocks are more or less completely altered, in that their component kinds of minerals and textures are transformed into other minerals or textures, or both." He considers weathering effects as, "strictly speaking," metamorphic; but, like de Lapparent, he felt no need of using "metamorphic" in systematic chapters dealing with the work of the atmosphere and the production of soils. Like Schuchert, his collaborator, and like nearly all other writers, Pirsson excludes the regolith, as well as gravels, sands, shales, etcetera, from the class of metamorphic rocks, thus implying a failure of the broader definition of metamorphism to match the needs of general geology. Pirsson recognizes two kinds of metamorphism, contact and regional, the latter covering (page 319) dynamic metamorphism "as a pronounced phase of it in one direction." He uses the expression "constructive metamorphism" for Van Hise's "anamorphism"—that is, recrystallization in the "zone of rock-flowage"—but adds (page 316) that simple downward pressure, "static pressure . . . appears to have little altering effect on rocks."

Ries and Watson (1915, pages 200-204) follow Van Hise in defining metamorphism "as any change in any rock, regardless of origin," thus including weathering changes in "alteration or metamorphism proper." They hold that static metamorphism and pressure metamorphism both "refer to quiescent conditions."

In their new book, Leith and Mead write (1915, page xvii): "Rock metamorphism is here defined to cover all mineralogic, chemical, and physical changes in rocks subsequent to their primary crystallization from magma. . . . We shall follow Van Hise by including under metamorphism not only development of schistose and crystalline rocks, but also all changes involved in rock weathering and cementation."

F. W. Clarke (1916, page 583) introduces his chemical discussion of the subject thus: "In its widest sense the adjective metamorphic may be applied to any rock that has undergone any sort of change. Practically, however, it is used to describe a well defined class of rocks in which the transformation from an original form has been nearly complete. A slightly altered igneous or sedimentary rock is not commonly called metamorphic; neither is a mass of decomposition products so designated. . . . Some varieties of metamorphism are entirely physical or structural, and therefore will not be considered in this memoir. Metamorphoses which represent only a development of slaty or schistose structure are of this kind. In most cases, however, metamorphism is accompanied by chemical changes, which are indicated by the production of new minerals, and this sort of metamorphism concerns us now. It may be regional, when large areas are affected, or a phenomenon limited to a contact between two reacting rocks; but these distinctions are of little significance chemically."

Dictionaries and encyclopedias reflect a diversity of usage similar to that illustrated in the foregoing extracts from standard works on geology.

The 1895 edition of the Century Dictionary (New York) gives this definition of metamorphism: "The process of metamorphosing or changing the form or structure; specifically, chemical change and rearrangement of the constituents of a rock by which they are made to assume new forms and made to enter into new combinations, the most important result of these changes being that the rock becomes harder and more crystalline in structure."

According to the Standard Dictionary (New York, 1895), metamorphism comprises "the changes that go on in rocks, due to recrystallization of their constituents, either with or without alteration in the chemical composition of the mass. The most important agents of metamorphism are *heat, moisture,* or other mineralizing factor, and *pressure.*" These are made active either by intrusion of igneous masses or by dislocations or movements of the earth's crust. Cementation by the enlargement of mineral grains is regarded as a metamorphic process. Static metamorphism is described as including "changes produced largely by pressure without great shearing or dislocation of the rock-masses."

The New International Dictionary (New York, 1904) regards metamorphism as covering only the "profound changes" in rocks and excludes weathering and decomposition. It recognizes only two kinds—contact and regional.

The New English Dictionary (Oxford, 1908) defines metamorphism as "the process of change of form or structure produced in a rock by various natural agencies" and adds: "*Metamorphic.* Of a rock or rock formation; that has undergone transformation by means of heat, pressure, or natural agencies"—an extraordinary solecism!

Flett, in the 1911 edition of the Encyclopædia Britannica, defines metamorphism as "the alteration of rocks in their structural or mineral characters by which they are transformed into new types." He excludes weathering, decomposition, and cementation. He admits two kinds: (1) "contact or thermal," and (2) "folding or regional," making no mention of load or static metamorphism.

DISCUSSION OF THE OLDER DEFINITIONS OF METAMORPHISM

A review of the literature thus shows that "metamorphism" has been used in at least five different senses.

1. Authors defining it as including "all changes" in rocks, after the original embodiment of those rocks as distinct masses of material, are: Durocher (1846), Kalkowsky (1886), Reyer (1888), Van Hise (1904), De Launay (1905), Kemp (1908), and Leith and Mead (1916).

2. Authors excluding weathering processes, but including cementation, are: Virlet (1847), Lossen (1872), von Hauer (1878), Green (1882), Phillips (1885), Teall (1888), Lawson (1888), Harker (1889), Roth (1890), the writers in the Century Dictionary (1895) and Standard Dictionary (1895), Dana (1895), A. Geikie (1903), the writer in the New

International Dictionary (1904), Hatch (1909), Rosenbusch (1910), Scott (1911), Becke (1911), Lindgren (1913), and probably Zirkel (1893).

3. Authors formally defining metamorphism in the broader sense, but in actual practice excluding weathering processes, are: de Lapparent (1893), Merrill (1897), Pirsson and Schuchert (1915), F. W. Clarke (1916), and Lahee (1916).

4. Authors excluding from the definition both cementation and weathering are: Lyell (1838), Chamberlin and Salisbury (1906), Haug (1907), Flett (1911), Tornquist (1913), Boeke (1915), and Cleland (1916).

5. Authors defining metamorphism in a broad sense and also in a narrower sense (excluding at least weathering processes) are: Studer (1847), Naumann (1850), Delesse (1857), Prestwich (1886), Grubenmann (1910), and Ries and Watson (1915).

None of the long list of writers has been guided by the strict logic of the literal etymology. In no case has rock folding been included among the metamorphic processes, though the mere folding of beds is a manifest transformation in a most literal sense. Thus, without exception, geologists have appreciated the uselessness of "metamorphism," if that word be given its broadest possible meaning.

Their right to restrict its meaning, in the interests of clear thinking and writing, is abundantly illustrated in the history of words. For the navigator, "chronometer" has not its literal meaning, but applies only to a very small class of time-keepers. Astronomers arbitrarily exclude comets and stars from the class of planets, the "wanderers." The architect's "dome," a synonym of "cupola," has only an indirect relation to the original Greek word, for the Greek house or temple was not in cupola form. The crystallographic "dome" is no more thoroughly entrenched in the English language because it recalls the actual form of the Greek *domos*. In zoology the meaning of "mollusk" is universally restricted far within the limits set by its etymology, and "metamorphosis" itself is as narrowed for technical biology as "metamorphism" has been narrowed by Lyell and many of his successors.

The degree to which strict etymology should be disregarded is, then, clearly a question of expediency. That it is difficult to answer in a way to win general consent is obvious to the student of definitions in the latest textbooks, dictionaries, and Government reports. The history of opinion during earlier decades is also somewhat discouraging; yet a critical comparison of the older and newer writings seems to suggest a way out of the present confusion.

In the first place, the great majority of geologists have, with Lyell himself, favored the exclusion of weathering from the group of metamorphic processes. Among the few who do not follow tradition is Van Hise, who, however (1904, page 163), emphasizes "the fact that the alterations in the belt of weathering are very different from [those in] the belts below." He continues: "In many places the change in the character of the alterations in passing from the belt of weathering to the belt of cementation is very sudden." Leith and Mead likewise distinguish a "belt of weathering" (perhaps better called a *shell* of weathering) wherein rock alterations are more or less sharply distinct from those induced at greater depths in the earth. The suggestion of Lindgren and others that the alterations properly referable to weathering are confined to the earth shell above the water table is a more precise expression of the same general idea and is worthy of special consideration as a possible criterion for distinguishing metamorphic changes from weather changes. That there are transitions between the sets of conditions leading respectively to ordinary rock-weathering and to the development of certain crystalline schists is not a compelling consideration. The existence of transitions in most natural phenomena ought not to, and does not, discourage the effort to classify. In their fundamental division of rock changes into katamorphic and anamorphic, Van Hise and his followers have not been deterred by the fact that both of these classes of alterations are displayed within the limits of a single rock body or even within the limits of an original rock-forming mineral. The lower boundary of the shell of weathering is certainly at least as definite as the boundary between the katamorphic and anamorphic shells.

The chief reason for the exclusion of weathering processes is, of course, to save the word "metamorphism," to prevent its overburdening. As used by the Van Hise school, it is equivalent to "alteration," and the more recondite word becomes practically useless. If these authorities were followed in this matter, two most useful words would become as unnecessary as they are, respectively, in Van Hise's "Treatise on Metamorphism" and Leith and Mead's "Metamorphic Geology." On the other hand, there is the utmost need for "metamorphism" as a designation for rock changes in depth, having nothing directly to do with weather alteration.

Weathering processes already demand whole volumes for their summarizing. The geological profession is not likely to agree with the proposal to consolidate that immense subject with the yet vaster one relating to rock changes under conditions of high pressure, high temperature, or both; nor are most geologists to be attracted by a definition of "metamorphic rocks," which are thereby made to include residual clays and soils, glacial deposits, shale, limestones, etcetera. Leith and Mead (1915, page 215), like Kemp (1908, page 144), are logically compelled to do this, but the result only goes to show the difficulties raised by their definition, for all geologists are vitally interested in the classification of rocks as well as in that of metamorphic processes.

Before attempting a definition that may meet the approval of the majority, a list of the alterations affecting rocks below the shell of weathering should be scrutinized. It covers:

1. Simple crushing.
2. Consolidation by pure cohesion.
3. Consolidation by cements, amorphous and crystalline.
4. Consolidation by both cementation and recrystallization.
5. Concretionary action.
6. Pseudomorphic changes in constituent minerals.
7. Polymorphic changes in constituent minerals.
8. Devitrification.
9. Recrystallization in general.
10. Volatilization; for example, dehydration, carbonization of organic matter.
11. Complete fusion or simultaneous solution of most of the rock constituents.

The simple crushing of a rock or its consolidation by pure cohesion, in neither case accompanied by new crystallizations, is not usually regarded as an independent metamorphic process. Both are very rare phenomena. Some mylonites and other breccias may represent the one, as a few stratified rocks may represent the other.

The problem of rock cementation is much more difficult. Most writers have, apparently, voted to regard it as a phase of metamorphism. Since cementation merges into load metamorphism with utter gradualness, and since the conditions of cementation are largely of the same quality with those controlling both load and dynamic metamorphism, this view of the majority seems well taken. For practical reasons, however, the writer believes it best to admit in true metamorphism only those kinds of cementation that are accompanied by new crystallizations in the rock body concerned.

By common agreement concretionary action, pseudomorphism, polymorphism, and devitrification are regarded as phases of metamorphism as well as of rock weathering.

Nearly or quite complete melting or solution of a rock, even though followed by crystallization, is usually treated as a magmatic, rather than a metamorphic, phenomenon. With that understanding the following definitions have been framed.

Opinion is divided concerning the place of mere volatilization without the formation of new crystalline matter. The change from lignite, through bituminous coal, to anthracite has been sometimes described as "metamorphic." Yet geological manuals and special works on coal, in describing this change, very seldom use the word. "Transformation" is there commonly preferred to "metamorphism," which is thus unnecessary in dealing with the coals. A mud is altered in composition by the expulsion of some of its water, and a bituminous sediment is altered by the expulsion of natural gas or oil; but few geologists are impelled to call either an instance of metamorphism. For reasons to be stated in a following section, it seems better to exclude all such cases of pure volatilization from the domain of metamorphism.

PROPOSED DEFINITION OF METAMORPHISM

If pure volatilization were included, metamorphism might be defined as the sum of the processes which, working below the shell of weathering, lead to the alteration of rocks through the activity of solutions—gaseous, liquid, or solid—the change in each case not being accompanied by general melting of the rock or by general simultaneous solution of its constituents.

If volatilization be excluded (as here advocated), metamorphism may be defined as the sum of the processes which, working below the shell of weathering, lead to the alteration of rocks through the *constructive* activity of *solutions*—gaseous, liquid, or solid—the change in each case not being accompanied by general melting of the rock or by general simultaneous solution of its constituents. More concretely, the definition may be phrased thus: *Metamorphism is the sum of the processes which, working below the shell of weathering, cause the recrystallization of the original crystalline materials in rocks (with or without chemical reactions) or the crystallization of original amorphous materials in rocks, the change in each case not being accompanied by general melting of the rock or by general simultaneous solution of its constituents.*

New crystallization in non-magmatic rock substance is the one basic principle that seems best to express the essential idea shared by Lyell and most other geologists since 1833. That petrographical criterion has its counterpart in the physico-chemical criterion of the alternative definition, namely, the proof of the constructive activity of solutions. The definition covers the unequivocal changes, such as those from granite to gneiss, from argillite or volcanic ash to schist, from limestone to marble, from argillite to hornfels. It covers also the change from coal to graphite, the change from anhydrite to gypsum, the change from calcareous mud to partly crystalline limestone, devitrification, and the consolidation of sediments when accompanied by the formation of crystalline cement. So defined, in terms of the *end result* of various processes, "metamorphism" has still an enormous extension in geology. The classification of those processes, founded on their fundamental causes, is the next step in a scientific description of metamorphism itself. Especially after one has tried to form a rigorous, yet practical classification, he realizes the value of restricting "metamorphism" in the measure just suggested. Only with completed analysis of this kind can the full meaning and validity of the necessarily abstract definition be appreciated.

DEFINITION OF "METAMORPHIC ROCK"

Perhaps a word as to its relation to the expression "metamorphic rock" may not be out of place. Every modern writer holds that not all rocks in which metamorphic processes have operated are to be technically called "metamorphic." Irrespectively of the definition of the key word, the class of metamorphic rocks groups only those that result from essential change in the *body* of each original rock. According to the proposed definition of metamorphism itself, this change must involve new crystallizations which are distributed through the rock body as a whole, affecting most or all of it. The criterion for a metamorphic rock is therefore double. When applied to the classification of rocks, there appears to be conflict with common usage in only one respect. A volcanic glass, completely devitrified in depth because of influences other than those connected with its original magmatic state, is logically to be assigned to the metamorphic rocks. This departure from tradition is intrinsically not a very serious matter, on account of the small volume of glass in the earth's crust. The assignment may be defended on the ground that a bed of graphite, derived from another kind of amorphous material, is regularly put in the class of metamorphic rocks.

CLASSIFICATION OF METAMORPHIC PROCESSES

REQUIREMENTS OF A WORKING CLASSIFICATION

An ultimate systematization of metamorphic phases would be based strictly on the origin of these alterations. Since the conditions of change are not fully known, the ideal is yet to be reached. The best classification now possible could represent no more than a summary report of progress in interpretation. Nevertheless, it should embody the minimum number of terms and definitions which can not apply after an indefinite expansion of knowledge on the subject. Every student of metamorphism knows the difficulty of framing definitions which are at once stable in the face of new discoveries and yet are of meaning intensive enough to match contemporary knowledge. Subdivisions should, moreover, be elastic enough to take in metamorphic phenomena whose causes are not now fully understood.

The problem of fruitful subdivision is specially insistent for field geologists. Hence the classification to be proposed is primarily geological. The dichotomous division into katamorphism and anamorphism may prove to have very great value in the description of rock or ledge. But, especially in field geology, an indication as to the controlling cause of a solutional change generally means much more than does a mere indication as to how the reactions ran in the solution. If increase of pressure is required to shift equilibrium in a given direction, the origin of the pressure increase may be immaterial to the student of the reaction as a purely physico-chemical change. On his part the geologist is deeply concerned with the cause of the pressure increase. Is it due to orogenic compression or to burial under a thickening cover of sediments or volcanic rocks? The professional injunction to answer such a fundamental question should be reflected in the main classification. If heightened temperature is the chief cause of new crystallizations in a rock, the geologist must go further than the physical chemist and ask whether the heating has resulted from the proximity of igneous masses or from orogenic crushing. In general, the physical chemist may be content with the laboratory report that a certain rock has been developed by anamorphic processes; the geologist is much more interested in the condition of the earth's crust which has led to that anamorphic assemblage of minerals.

The prevailing classifications do, in fact, aim to meet this chief requirement on the part of the geologists. The deeper meaning of metamorphism as one aspect of the development of the globe as a whole has given life to such widely used terms as "dynamic metamorphism," "static metamorphism," "load metamorphism," and "contact metamorphism." So firmly fixed are these, no acceptable classification is henceforth likely to dispense with most of them, if indeed with any of them.

Unfortunately, each of the names already given to different phases of metamorphism has, like the key word itself, had varying definitions. It becomes necessary in each case to decide what is the most advisable definition before incorporating that term in the system.

As a general rule, the phases of metamorphism have been given names that must be arbitrarily defined, else they would have been nearly or quite useless. Objection has been made to "dynamic metamorphism" on the ground that all metamorphism means movement—of mass or molecule. The same principle would destroy "pressure metamorphism," for all metamorphism takes place under some pressure, and "load metamorphism," for all metamorphism takes place under some load. In a literal sense nearly all metamorphism is "hydro-metamorphism," since water is a participant in most recrystallizations in rocks. Similarly, all metamorphism is "thermal metamorphism," for some heat is indispensable throughout. Happily, the inventors of the names here considered have not been bound by verbal form. They have treated words as tools and not as masters; as representative and not as directly connoting all the ideas symbolized by the individual words.

A brief survey of the varieties of usage will aid in choosing, for some of the terms employed in the proposed classification, those definitions that seem best to meet the present and future needs of geological science. After that review, a few other expressions appearing in the scheme will be introduced and discussed.

DEFINITION OF REGIONAL METAMORPHISM AND LOCAL METAMORPHISM

Three different meanings have been assigned to "regional metamorphism." Its originator, Daubrée (1860, page 59), did not define it formally. As already noted, he saw in it an improvement, as a synonym, on the "normal metamorphism" of de Beaumont, Virlet, Naumann, and others. Daubrée thus seems to have intended the expression to cover only those changes in rocks which are due to simple burial and the emanation of heat or hot gases from the earth's interior. In this sense Brauns (1896, page 278), Termier (1903, page 581), Doelter (1906, page 175), Coleman (1910, page 615), and Tornquist (1913, page 18) use the term.

Prestwich (1886, page 408), Teall (1888, page 418), de Lapparent (1893, page 1574), Rosenbusch (1910, page 72), Scott (1911, page 409), Flett (1911), page 219), and Holmquist (1916, page 145) define or use it as equivalent to "dynamic metamorphism."

A. Geikie (1903, page 766), Kemp (1908, page 113), Pirsson (1915, page 319), Ries and Watson (1915, page 208), and F. W. Clarke (1916, page 583) describe regional metamorphism as that kind which, by its nature, is likely to affect *extensive areas,* and do not inject into its definition any reference to the cause of the alteration beyond the statement that the rock alteration is *not genetically connected with the eruption of magma.*

The third definition has many adherents other than those just named. They have felt the necessity of a term with just this limited connotation, simple and somewhat negative as it is. Abundant experience has set up special claims for their definition—claims so strong that its retention in a working classification seems highly expedient.

The correlative term *"local metamorphism"* is preferable to "contact metamorphism," for a reason to be more fully seen in a following section on "load-contact metamorphism." Many Precambrian terranes have been metamorphosed by a combination of causes involving both igneous intrusion and widely spread, truly regional conditions of recrystallization, namely, those of load metamorphism. One can not say whether the necessarily local, igneous-rock influence or that of load cooperating with general earth heat is the more important. It seems best, therefore, to group both load metamorphism and load-contact metamorphism under the one head of local metamorphism, which is thus defined as *metamorphism genetically connected with the eruption of magma.*

Like "regional metamorphism," the term "local metamorphism" may yield its place when origins have become sufficiently ascertained. Until that distant day each will continue to serve a most useful purpose as one member in the grand, dichotomous division of all metamorphic processes.

DEFINITION OF DYNAMIC METAMORPHISM

Rosenbusch's definition of dynamo-metamorphism has been given above. He added (1910, page 73) the following statements: "That it effects immediate changes in the structure of the rock concerned—through stress, crushing, displacement, stretching, cleaving—can not be doubted; whether it directly causes chemical alteration is not fully proved, but probable. In any case it facilitates the access of transforming agents and extraordinarily increases the amount of surface on which those agents may act. Thus in dynamo-metamorphism we have displacement in the rock and the development of a new structure" (translated).

Harker (1889, page 16) supplements Rosenbusch's definition with the theoretical view that the term should imply conditions of low temperature and high pressure.

De Lapparent (1893, page 1406) understood dynamic metamorphism as resulting "from the mechanical actions (French, 'actions') to which the solid rocks are subjected during the building of mountains." On page 1573 he remarked: "The orogenic action does not seem to be limited to the production of mechanical effects. It appears to have been also a potent cause of metamorphism." On page 612 a formal definition is given as follows: Dynamic metamorphism is "the sum of the changes which orogenic movements have occasioned, either in compressing and dislocating the minerals or in facilitating the circulation of hot waters, capable of reacting on the mineral species existing in the rock." De

Lapparent evidently thought that the term should mean much more than pure crushing.

Zirkel (1893, I, page 604) was of opinion that "dynamo-metamorphism," as denoting merely the participation of a force, is a too general name.

Termier (1903, page 580, and 1910, page 588) considers that dynamic metamorphism "deforms but does not transform," and has strenuously advocated its disuse in scientific writing. Grubenmann (1910, page 125) also recommends its abolition, since, in his opinion, the name leads to the wrong notion, that mere pressure suffices for the rock alterations observed in mountain-built areas. Van Hise (1904, page 763) holds that the term is "objectionable for many reasons"; that "fracturing in the belt of cementation is equally dynamic metamorphism," and that (page 39) "in an exact sense all metamorphism is dynamic . . . dynamo-metamorphism refers to conditions of motion." Leith and Mead (1915, page 207) make "dynamic metamorphism" a rigorous synonym of "rock flowage." Similarly, Lahee (1916, page 231) regards the development of schistosity at right angles to the vertical stress of mere load as one type of dynamic metamorphism.

Without further extracts from the recent literature, a serious divergence of view is obvious. Termier's position can be understood only on the supposition that he defined "metamorphism" in a manner unacceptable to most geologists. More specifically, he does not regard new crystallizations as implied in the use of this key word; neither does he follow the definition of dynamic metamorphism given by Rosenbusch and practically adopted since 1889 by the majority. Termier's statement (1903, page 581) that "dynamic metamorphism . . . does not exist" depends on an arbitrary and hardly defensible definition of the term. Grubenmann's objection to it loses weight if it be recognized that "metamorphism" itself implies the activity of solutions; the idea that pressure alone is involved in the dynamic phase is automatically excluded. The objections by Van Hise and Zirkel, founded on a too inclusive use of the word "dynamic," have already been discussed; all progress in classification is impeded if the meaning of adjectives or noun be fixed by literal etymology.

How far such a technical expression as "dynamic metamorphism" bears its meaning on its face depends on the meaning to be assigned to its correlative or negative in scientific classification—in this case, "static metamorphism." In the mind of the average geologist using both terms is a more or less distinct picture of the thing which "moves" or "stands." That thing is the earth's crust. One set of metamorphic conditions accompanies strong movements of the crust. Another, not necessarily quite different, set controls regional metamorphism in the absence of strong crustal movements. These two conceptions, ruling in the geological profession, together suggest the definition of dynamic metamorphism as *metamorphism which is induced in rocks because of their deformation, the crustal movement being of the orogenic type.*

The proposed definition has the advantage of not being too intensive for general acceptance. It does not state the physical chemistry involved. It does not presuppose an increase of temperature, however general such increase may be during mountain-building. It does not presuppose an enforced, special circulation of water or other fluids; nor does it by any means cover all instances where the changing rocks have undergone crushing or mere increase of pressure. The one essential, and perhaps the only unassailable criterion, for dynamic metamorphism is its genetic relation to *orogenic* movement, the transfer of large masses of the earth's crust. According to the suggested definition, the mental picture called up by the use of the term is a geological picture, as it should be. The single genetic condition emphasized is in ultimate control of the reactions leading to chemical equilibrium in the rocks; but it is also the supreme fact for the general geologist who is studying the given region or is reading the reports of others about that region. So restricted, the name "dynamic metamorphism" may be saved for science and serve as a perfect counterpart of that other most useful name, "static metamorphism."

DEFINITION OF STATIC METAMORPHISM

Judd (1889, pages 243-246) introduced the expression "statical metamorphism" to designate the rock changes resulting from "chemical and crystallizing processes which certainly go on at great depths, and under enormous pressures, even when the rock-masses do not yield to the pressures and thus become subjected to the movements which result in dynamo-metamorphic action. Such changes, resulting from pressures that do not affect movements in the rock-masses, may be appropriately called 'statical metamorphism.' . . . The most potent agency by which change is effected consists in the penetration of the whole mass of the rock by various liquid or gaseous solvents. It is for the whole group of such changes—of which 'schillerization' is a conspicuous example—that I propose to employ the term *statical* metamorphism." He noted that statical metamorphism may either precede or follow dynamic metamorphism, and that the latter is much less important than was generally thought at the time of his writing.

Dana (1895, page 440) described "statical metamorphism" as that "dependent on heat of a statical source—the earth's mass and the vapors about it."

Geikie (1903, page 805) speaks of the "statical phase" of regional metamorphism as that connected with "enormous pressure leading to little or no molecular crushing, but with some shearing movement in the rock." He remarks that it "does not produce such striking results as the . . . dynamical phase."

Van Hise (1904, page 47) wrote: "Metamorphism by molecular movement has generally been called static metamorphism."

Ries and Watson (1915, page 204) note simply that static metamorphism refers to "quiescent conditions."

Here, again, there is no consensus of opinion. Judd specified that "the rocks do not yield to the pressures [exerted by thick covers]." Geikie assumes such yielding, for there is "some shearing movement in the rock," though he makes the cryptic remark that the pressure leads to "little or no molecular crushing." Judd stressed the work of fluid solutions. Dana stressed the influence of the earth's internal heat. Van Hise regards molecular movement as the essential feature.

Solutions, heat, molecular movement, and some yielding to pressure are necessary characteristics of all kinds of metamorphism. The residual condition, which may be taken as a workable criterion, is the absence of deformation of the orogenic type. Accordingly, as already implied, static metamorphism may be defined as *that phase of regional metamorphism which is not induced by orogenic deformation.*

Contact metamorphism is usually, in a literal sense, also "static," inasmuch as alterations by magmatic heat and gases are not conditioned by crustal deformation. The proposed restriction of meaning for "static" is therefore arbitrary, but no published name other than "static metamorphism" so well expresses the required negative of "dynamic metamorphism," just delimited. As a couple the two definitions are logical, and the corresponding terms can directly tell what the geologist most needs to know concerning the principal condition for the regional alteration of rocks.

PHASES OF STATIC AND DYNAMIC METAMORPHISM

Supported to a considerable extent by traditional usage, one may thus divide all metamorphic processes into two primary classes, symbolized by the expressions "regional metamorphism" and "local metamorphism"; and also divide regional metamorphic processes into secondary classes, symbolized by "static metamorphism" and "dynamic metamorphism." Further logical subdivision is not so well guided by the principle of long usage and is intrinsically more difficult. Nevertheless, more intensive terms are urgently needed to portray the existing state of knowledge and to provide for the description and discussion of metamorphism in the future.

All metamorphism is due to the activity of solutions. Hence the factors to be used in distinguishing ternary and still lower classes of metamorphic processes may well be of physico-chemical nature. If these finer subdivisions can be so made, the more purely geological factors appearing in the primary and secondary categories, a full genetic scheme is possible.

The march of crystallization in a rock depends on temperature, pressure, the presence of liquid and gaseous solvents, and the chemical composition of the rock as a whole; for none of these factors are the quantitative data sufficient to allow its rigorous application to the present problem, and it is hopeless to expect an adequate collection of the data for generations to come. The vocabulary of metamorphism is poverty-stricken for a very good reason. It lacks in names for the respective subdivisions of dynamic, static, contact, or load contact metamorphism, if made on the basis of any one of the four physico-chemical factors; nor is there at present any apparent need of spinning the web of classification so elaborately. Nevertheless, the content of either static metamorphism or dynamic metamorphism is so huge that their further subdivision is already advisable.

In the present state of knowledge temperature may be assumed as the most appropriate factor for the ternary, genetic subdivision. The static metamorphism of rocks situated at comparatively small depths takes place *at low temperature and is possible only in the presence of water or other fluids with low freezing-points.* Cementation or lithifaction, when dependent on new crystallizations, is metamorphism of this sort. It may be designated as *hydrometamorphism* (see Harker, 1889, page 15; Merrill, 1897, page 161; Lindgren, 1905, page 124), if the name be understood as applying to changes in rocks not subjected to orogenic stress during the metamorphism. This use of the word is arbitrary, inasmuch as certain hydrous formations have been partially recrystallized during their deformation yet without the development of high temperature. No unequivocal synonym has been found in print. To supply one, the expression *"stato-hydral metamorphism"* has been coined.

The corresponding alteration *under dynamic conditions, but at low temperature,* may be called *"dynamo-hydral metamorphism."* A simpler name might be *"slaty metamorphism,"* since certain slates have been so developed. However, other slates have been formed at temperatures that can not be called low; hence this adaptation is not wholly satisfactory.

The analogous term *"stato-thermal metamorphism"* has been coined to mean *regional alteration under static conditions and at high temperature.*

Its simpler synonym is Milch's *"load metamorphism."* "Load metamorphism" directly connotes vertical stress, but just as truly also high temperature. New crystallization controlled by dead weight can not take place except at deep levels, where the rocks feel strongly the internal heat of the earth. This type of alteration has been perhaps the most important of all; yet recent writers, over-enthusiastic about dynamic metamorphism, have strangely overlooked it or else left it without due emphasis. Hence a following section of this paper is specially devoted to load metamorphism.

The fourth member of the ternary series may bear the name *"dynamo-thermal metamorphism."* This is regional metamorphism *under dynamic conditions and at high temperature.* A simple synonym is hard to find, but Gosselet's (1883, page 202) term *"friction metamorphism"* might be revived for the purpose. It should, however, be used symbolically, with proper guarding, for friction is clearly not the sole cause for the high temperature so often operative in purely dynamic metamorphism.

The suggested ternary subdivision is imperfect. It depends on a distinction between "low temperature" and "high temperature"—one that can not yet be made, in practice, on a quantitative basis. Nevertheless, there is some advantage in so enlarging the vocabulary of metamorphism that temperature control may be, at least approximately, indicated in accounts of recrystallized rocks.

DEFINITION AND SANCTION OF "LOAD METAMORPHISM"

Geology owes to Milch (1894, page 121) an important paper, in which two kinds of regional metamorphism are described and named. The first is called "Dislocationsmetamorphismus," Lossen's old name for what most geologists call dynamic metamorphism, originating in pressure directed tangentially with respect to the earth's curved surface. The second is called "Belastungsmetamorphismus," with the exact English translation, "load metamorphism." This type originates in "verticale Belastung." Milch holds that load metamorphism "is represented in the development of every rock; it changes every rock which is not in process of destruction by weathering agents."

Milch points out that dynamic and local metamorphism result in very similar or identical kinds of mineralogical composites, because each phase may entail the same physico-chemical conditions underground. Through load metamorphism he explains the ubiquity of the "Grundgebirge" and the very common parallelism between original stratification planes and schistosity planes in metamorphosed sediments. He believes also that in some instances load metamorphism can induce planes of schistosity crossing the bedding of sediments which had been upturned before their final recrystallization was completed.

In a later paper (1910, page 44) Milch shows the likeness between load metamorphism and the "normal metamorphism" of de Beaumont and the "regional metamorphism" of Daubrée.

Brauns (1896, page 278) adopts "Belastungsmetamorphismus," giving "regional metamorphism" as synonym; he notes the strong contrast of both to "dynamic metamorphism" in meaning.

After many years of field-work in the older Precambrian (Shuswap) terrane of British Columbia, G. M. Dawson (1901, page 64) concluded that "the foliation of the Shuswap rocks may have been produced rather beneath the mere weight of superincumbent strata than by pressure of a tangential character accompanied by folding." In his summary of British Columbia geology, he continues with the remark: "In the Archean of eastern Canada, foliation still nearly horizontal or inclined at low angles often characterizes considerable areas and appears to call for some explanation similar to that above suggested [for the Shuswap rocks]."

While mapping the later Precambrian (Beltian) formations of southern British Columbia and Alberta, the present writer independently came to the view that load metamorphism is of superlative importance. Later work in the Shuswap terrane itself confirmed that conclusion, in which the writer found he had been anticipated by Dawson, as well as by Milch, who first gave this general process its name.[3]

In eloquent addresses to two international congresses, Termier (1903, 1910) uttered timely protests against exaggerated claims for dynamic metamorphism. His reasoning was based on his experience in the western Alps. Translated, his words (1903, page 580) are: "Wide areas of the Alps seem to have enjoyed relative tranquillity and, in any case, to have undergone neither intense folding, nor crushing, nor cleaving. . . . And, nevertheless, the metamorphism of the crystalline terranes is as intense as elsewhere." He believes their rocks had already become crystalline schists before the great foldings and overthrusts characteristic of the Alps took place. The relations are like those observed in nature by Dawson, Milch, and others; but Termier preferred to use, in explanation, the older term "regional metamorphism" to Judd's "statical metamorphism" or Milch's "load metamorphism." In fact, Termier emphasizes the rise of juvenile gases with the consequent heating of geosynclinal strata, rather than vertical stress, as the controlling condition of the recrystallization.

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[3] See summary reports of the Geological Survey of Canada, 1911, page 168, and 1912, page 159; also memoirs of the Geological Survey of Canada, number 38, 1912, page 172, and number 68, 1915, page 44.

In spite of the clear announcements of the principle by Dawson and Milch, many geologists of the present day are still far from sympathetic with the idea of load metamorphism. Very rarely is it even mentioned in works on rock changes or on the crystalline schists. Of the few authors who have considered vertical stress in relation to the development of schistosity, a number like A. Geikie, Van Hise, and Pirsson express doubt that there is any important positive relation between them. For these reasons a sketch of the field facts, suggesting the reality and great significance of load metamorphism, may not be without warrant. The value of a classification of the phases of metamorphism really depends in no small part on a wise decision in this matter.

A strong, perhaps the strongest, argument for load metamorphism is expressed in the foregoing quotations from Dawson and Termier. Extensive areas in western Canada, eastern Canada, and the western Alps, though underlain by typical crystalline schists, display no evidence of ever having been greatly affected by crustal deformation. Bedding is perfectly preserved in the sedimentary members of the crystalline groups of rocks. The dip is characteristically low, even nearly horizontal, over wide stretches. The structure is that of a plateau, a somewhat broken plateau.

Besides the examples in the Belt terrane and Shuswap terrane of the American Cordillera, in Ontario, and in the Alps (compare Lory, 1888, page 87 ff), many others are on record. In this list of regions are notable tracts in Labrador (Low, 1895, page 199); the Adirondacks (Cushing, 1914, page 30; W. J. Miller, 1914, page 59, and 1916, page 587); Greenland (A. Heim, 1911, page 180); the Gföhl gneiss of the Lower-Austria Waldviertel (Becke, 1910, page 617); the Erzgebirge (Lepsius, 1903, pages 89, 99, 108); the Schwarzwald (Schwenkel, 1912, pages 139 and 253); the Oban-Dalmally district of Scotland (Kynaston, 1908, page 21); German East Africa (Schmidt, 1886, page 451, and Bornhardt, 1900, page 459); Rhodesia, Congo State, and Uganda (Mennell, 1913, page 205).

With a few exceptions, the authors mentioned do not consider in print the cause of the plateau structure in the respective gneisses and schists. The extreme advocates of dynamic metamorphism would find it in "rolling-out," "overturning of folds," "multiple thrusts," or intense horizontal shearing. In the fields studied by the writer none of these explanations can be admitted. As Dawson clearly saw, the only feasible explanation of the schistosity in the flat-lying Shuswap rocks is dead-weight stress controlling their recrystallization. Supported also by the opinions of Milch, Termier, Lory, Becke, and Schwenkel, it is not altogether rash for one to assume that load has been a main factor in the metamorphism of many of the plateau terranes listed.

Again, for some schistose formations which have been greatly dislocated, there is good evidence that the principal metamorphism was accomplished before the main foldings or faultings. An unusually vivid instance is found in the British Columbia Shuswap terrane. On its gneisses and schists rest, in nearly perfect structural conformity, the extremely thick Beltian sediments. These, nearly or quite conformably, pass upward into the Cambrian series. All three rock groups have been upturned in post-Cambrian time. Some of the Cambrian beds, much of the Beltian series, and almost all of the Shuswap sediments and eruptives had been thoroughly recrystallized before the upturning. That deformation caused new, *quite local* dynamic metamorphism, but left the original schistosity largely unchanged. The post-Cambrian orogeny seems to have had nothing to do with the principal schistosity.

A similar relation prevails in the Erzgebirge, Vogtland, the Fichtelgebirge, and East Thuringia, where the "Archean" gneisses and schists pass up, concordantly, into thick phyllites, and these up into fossiliferous Cambrian sediments (Credner, 1897, page 396; Lepsius, 1903, page 108; Rosenbusch, 1910, page 577).

Lory (1888, page 87) described it in the Monte Rosa district of the Alps.

A third reason for crediting the great efficiency of load metamorphism is the exceedingly common parallelism between foliation or schistosity and the stratification. This fact is abundantly illustrated in the Canadian shield, in the Adirondacks of New York State, and in the Precambrian of the North American Cordillera, Scotland, Scandinavia, Finland, etcetera. Löwl (1906, page 50) has given a good statement of it in the following passage (translated): "The great majority of the crystalline schists are foliated, not across the bedding, but parallel to it. Their parallel texture must have been developed when the rocks lay undisturbed, and thus only because of the downward pressure of the overlying rocks, exactly as in the case of shale and most clay-slates, among which, indeed, transverse cleavage is not the rule, but the exception. It is not merely a case of the condensation of the buried rock by the dead weight of its cover. The load also causes foliation. Its effect is not hydrostatic, but, even if there be pressure on all sides, the pressure in the vertical direction is the strongest. Lateral thrust may develop still greater inequality of pressure, especially at small depth; yet an essential difference between the effects of load and lateral thrust is not to be assumed."

Parallelism of schistosity and bedding, to the degree observed in the crystalline schists, is truly inexplicable by pure dynamic metamorphism. The parallelism is found, whether or not the dips are persistently low or high or persistently changing across-country. Since new metamorphic minerals seem to be regularly elongated at right angles to the metamorphosing stress, the schistosity produced by intense orogenic movements (tangential force) will be parallel to bedding only in comparatively rare and narrow belts. Prevailing parallelism in a terrane of variable dip is therefore a good indication that dynamic metamorphism has not controlled the recrystallization. Elementary as it is, this principle has been wonderfully neglected in most of the recent discussions of regional metamorphism.

A fourth argument, connected with the last, has independent power. In the Shuswap terrane, in the Precambrian of eastern North America, and in many other schist areas the crystallinity or degree of metamorphism is, to a large extent, not directly related to the amount of crustal deformation. Many vertically dipping schists are practically identical in habit, including size of grain, with neighboring, little-deformed schists of the same chemical composition. For this fact the assumption of load metamorphism, active before the mountain-building, offers the only explanation yet proposed.

Of course, a rock series already recrystallized by load metamorphism may be affected by later alterations of dynamic origin. Beautiful examples are visible among the Shuswap rocks (Daly, 1915, plate 21). Such superposition of metamorphisms may thus obscure the whole problem of origins. In fact, its solution has doubtless been retarded because special students of metamorphism have so largely worked in fields where schists and gneisses happen to have been much dislocated since the recrystallization of those rocks. Most workers have not sufficiently canvassed the question as to what was the condition of each rock formation *before* upturning. The proof of recrystallization in zones of intense dynamic stress has too easily led to generalizations as to the genesis of the rest, often the greater part, of the same terrane, where crustal deformation has been less or where its causal connection with the visible metamorphism can not be demonstrated.

Finally, the fully significance of load metamorphism is not understood until its relation to the doctrine of uniformitarianism has been made out. Koenigsberger (1910, page 651) and Ries and Watson (1915, page 203) deny that deep burial has caused regional metamorphism, on the ground that many Paleozoic and younger strata, though once covered by thousands of meters of rock, have not been changed to crystalline schists. The present writer (1912, page 479) has observed a nearly complete absence of recrystallization in the Lower Cretaceous arkose and shale of the Pasayten series in British Columbia. Yet those beds were formerly beneath younger Cretaceous sediments probably more than 8,000 meters thick. A similar condition is reported for the basal beds of the Cretaceous geosynclinal of northern California, where the thickness of cover was likewise colossal.

Such examples do show the subordinate importance of load metamorphism in later geological time. To a somewhat smaller extent the Paleozoic geosynclinals fail to exhibit recrystallization in their lower strata. The pressure has been high, the water content considerable, the composition of the sediments appropriate, the deep burial of long duration; and yet metamorphism has been partial or nil.

The latest Precambrian (Beltian) strata, on the other hand, are largely recrystallized at horizons which have never been buried deeper than those reached by the non-crystalline Mesozoic and Paleozoic sediments just mentioned. The pre-Beltian stratified formations, from bottom to top, the world over, have been almost entirely recrystallized.

From Clarke's (1916, page 30) calculation of the whole amount of rock that has ever been decomposed by the weather it is easy to form a rough idea of the total volume eroded in geological time. But a fraction of this total can be assigned to Precambrian time. Of that fraction only a part represents the covers that lay on the surfaces of unconformity between the later Precambrian series and the older complexes of crystalline schists. The complexes were highly metamorphic before the ancient denudation corresponding to each of the unconformities. The combined areas of the known complexes form a vast total. Much greater is the total area of similar Precambrian terranes, reasonably supposed to underlie the existing Paleozoic and younger sediments. It seems safe to hold that the average cover on the complexes at the time of their recrystallization was far less than 5,000 meters in thickness. Hence, if that change were induced by vertical stress, the conditions must have been quite different from those which have ruled since the beginning of the Paleozoic.

Assuming a steeper thermal gradient for the earth in the pre-Beltian era, as well as load metamorphism under a moderate cover, the ancient recrystallization of the Shuswap terrane has been explained. In somewhat less concrete form the idea is found in writings as old as Hutton's. It has been lost to sight by too many of the modern advocates of dynamic metamorphism. A speculation involving the conception of an earth originally very hot near the surface is no more dangerous than the fashionable explanation of all, or nearly all, regional metamorphism by orogenic movements. More probably than any other, the conception of load metamorphism affords a useful starting-point in the problem of the Precambrian crystalline schists.

The five arguments outlined are of unequal strength, but their cumulative power is great. In any case it seems eminently wise to provide load metamorphism a place in a general classification of rock changes, if that classification is to meet the needs of geologists who have to deal with the Precambrian formations.

DEFINITION OF "DYNAMO-STATIC METAMORPHISM"

A special combination of static and dynamic conditions is worthy of recognition. A rock formation which has become *covered by a thick overthrust mass may itself not be crushed or otherwise deformed and yet may be recrystallized because of the new load on it.* If so, the temperature being necessarily high and the pressure on the recrystallizing rocks being vertical, the process is an example of load metamorphism, while the special inciting cause is dynamic. To distinguish such a case, the name "dynamo-static metamorphism," symbolizing a third principal subdivision of regional metamorphism, may be employed.

DEFINITION OF CONTACT METAMORPHISM

Contact metamorphism comprises all metamorphic changes due to contact with or proximity to any body of eruptive (igneous) rock, the new crystallizations not being definitely directed by dead-weight stress. This definition, adapted from Geikie (1903, page 766), is that generally followed by geologists.

Certain authors have tried to restrict the term to mean the effects of mere heating by eruptive magma. Thus de Lapparent (1893, page 1402) used "métamorphisme périphérique" to symbolize the metamorphism induced by gases and liquids emanating from magma and included it with "métamorphisme de contact" in a dichotomous division of "métamorphisme d'influence." Haug (1907, page 176) appears to agree in this usage. Von Wolff (1914, page 240) makes "contact metamorphism in the narrower sense" a synonym for this purely thermal contact action.

On the other hand, Boeke (1915, page 384) reverses the definition and regards "Kontakt-Metamorphose" as that due to the recrystallizing influence of magmatic fluids on the invaded rocks, while his "Thermometamorphose" is that induced when high temperature plays the chief rôle at igneous contacts.

Inasmuch as it is, in many instances, impossible to distinguish the effects of mere heating from those of gaseous emanation, most geologists have been right in refusing to use either principle as a criterion for contact metamorphism, and, expressly or tacitly, have used the name with the broad meaning given above. Their view is reflected in the definitions given in the geological manuals of Dana, Geikie, Tornquist, Pirsson and Schuchert, Cleland, and many others. The term is thereby made essentially synonymous with the French "métamorphisme d'influence" and with the older names "abnormal metamorphism" and "accidental metamorphism."

Barrell (1907, page 116) separates contact metamorphism from contact metasomatism. The former is described as "taking place without addition of materials and resulting in a crystallization of the wall rocks." The changes are "those of volume and not of mass." Contact metasomatism "indicates a mass change in the composition of the rock other than the elimination of gases involved in simple metamorphism. The action takes place through magmatic emanations." These usages conflict with the definition of metamorphism here proposed and also with definitions of contact metamorphism by the majority of writers (for example, Grubenmann, 1910, page 70), who regard magmatically controlled metasomatism as a true metamorphic phenomenon.

V. M. Goldschmidt (1911, page 119) describes a mere recrystallization of the country rock, without the addition of material to it from the magma, as "normal contact metamorphism," and describes alteration of the country rock through such addition of material as "pneumatolytic contact metamorphism." Von Wolff (1914, page 240) adopts the latter name with Goldschmidt's definition.

Bunsen's (1851, page 241) "pneumatolytic" referred to sublimations from truly volcanic masses. Brögger (1890, page 213) enlarges its meaning so as to take in all the metamorphic changes due to magmatic gases in general. Barrell (1907, page 117) suggests that "contact metasomatism may be divided into pneumatolitic (sic) and hydrothermal metasomatism, according to whether the magmatic emanations are above or below 365° C. and 200 atmospheres pressure—the critical temperature and pressure of water." In principle Irving (1911, page 298) follows this usage. It raises the question whether the field of contact metamorphism might be divided into three parts: *thermal-contact* metamorphism, covering rock changes due to mere heating; *hydrothermal-contact* metamorphism, covering rock changes involving magmatic fluid emanations at temperatures less than 365° C.; and *pneumatolytic-contact* metamorphism, involving gases at temperatures above 365° C. This query seems best answered in the negative. First, because present knowledge does not permit the distinction in practice on the basis of the given temperature; secondly, because the exclusion of many reactions, controlled by vapors and true gases, from the domain of pneumatolysis causes a highly arbitrary and apparently quite unnecessary departure from the literal meaning of "pneumatolysis"; lastly, because connate fluids of the country rock, which have metamorphic effects very similar to those exerted by magmatic emanations, are not considered in the subdivision.

According to another conceivable classification, "*hydrothermal-contact* metamorphism" might be defined as metamorphism controlled by water and its accompanying vapor, while "*pneumatolytic-contact* metamorphism" includes the types of contact metamorphism controlled by other volatile substances. "*Thermal-contact* metamorphism" would be defined as before. This scheme also is hard to apply in nature, and it does not agree with the concept of pneumatolysis which, vague as it is, now rules in the minds of most geologists.

In the present connection it should again be noted that existing criteria do not in many cases suffice to distinguish, practically, "thermal-contact" effects from those controlled by gases and vapors.

In fact, the writer has been unable to find in the literature any suggestion of a satisfactory subdivision of the contact-metamorphic processes. The importance of the subject in the theory and description of ore deposits is manifest. Perhaps the group of economic geologists will yet develop a truly scientific classification, with corresponding definitions, for the phases of contact metamorphism.

DEFINITION AND SANCTION OF "LOAD-CONTACT METAMORPHISM"

Extensive masses of the older Precambrian rocks are composites of sediments or surface volcanics with injections of igneous material. Generally granitic in composition, the intrusives commonly favor the form of the sill or laccolithic sheet. So numerous are these bodies that their total contact-metamorphic effects are profound. In some cases the changes wrought are those of pure contact-metamorphism. In very many others the recrystallization of the invaded formation has been simultaneously controlled by the weight of its cover. *The influences of vertical stress, of the earth's general heat, and of the injected magma are thus concurrent. New crystallizations in the country rock are caused by a combination of causes which may be called "load-contact metamorphism."*

The writer first began to appreciate this compound type while studying the Shuswap terrane of British Columbia, with which a comparison of Precambrian rocks in Ontario was later made in the field. Where the siliceous sediments, limestones, and basic volcanics of the western terrane are not charged with igneous injections in great number, the rocks are seen to have been recrystallized by pure load-metamorphism. In other areas, where the same formations were split by many granitic sills, the invaded rocks have quite different habit. The grain is characteristically much coarser. The mineralogical composition is somewhat unlike that observed in the sill-free parts of the terrane. Nevertheless, the invaded rocks are usually schistose in high degree; the planes of schistosity are here, also, sensibly parallel to bedding planes, and the directing influence of overlying load is as clear as elsewhere. The sediments appear to have been recrystallized by pure load-metamorphism before the epoch or epochs of sill injection. If so, this is another instance of superposed metamorphisms. However, the evidence for a combination of contact and load influences in the later metamorphism of the sill-charged strata is clear. In fact, load metamorphism continued after the freezing of the sills, for most of these are now orthogneisses, with schistosity planes parallel to the sill contacts and to the planes of bedding in sediments and volcanics. An influence which so fully controlled the recrystallization of a comparatively stable assemblage of minerals, like granite, could not fail to direct the recrystallization of the strata alternating with the sills.

The writer suspects that load-contact metamorphism is largely responsible for the development of Precambrian gneiss-schist complexes in general. The sanction for the new term and for its definition depends in part on the strength of the reasoning by which belief in pure load-metamorphism has been won. Using both principles, or at any rate keeping an open mind on the question of their validity, one is better equipped for an attack on the problem of the crystalline schists.

PROPOSED CLASSIFICATION

The following table gives the suggested division of metamorphic processes, each name bearing the preferred definition:

A. REGIONAL METAMORPHISM (not caused by eruptive bodies).
  I. *Static metamorphism* (orogenic movement not a causal condition).
    1. *Stato-hydral* metamorphism or *hydrometamorphism* (low temperature).
    2. *Stato-thermal* metamorphism or *load* metamorphism (high temperature).
  II. *Dynamic metamorphism* (orogenic movement a causal condition).
    1. *Dynamo-hydral* metamorphism or *slaty* (?) metamorphism (low temperature).
    2. *Dynamo-thermal* metamorphism or *friction* (?) metamorphism (high temperature).
  III. *Dynamo-static metamorphism* (load metamorphism in rocks lying beneath overthrust masses).

B. Local metamorphism (caused by eruptive bodies).
  I. *Contact metamorphism* (magmatic influence in control).
  II. *Load-contact metamorphism* (combination of load and magmatic influences).

ATTEMPT AT AN ALTERNATIVE CLASSIFICATION

With this scheme in mind, the ground for the exclusion of pure volatilization from the list of metamorphic processes may again be profitably considered. The question is whether it is expedient to regard as technically metamorphic rock changes that are typified by the conversion of soft coals into anthracite and by the mere expulsion of water from buried mud. In order to discuss this enlargement of the conception of metamorphism, a special name for changes through pure volatilization is desirable. The expression "alembic metamorphism" is suggested for the purpose.

Pure distillation takes place under the conditions of static, or dynamic, or contact metamorphism. In a similarly tentative way, let these phases of pure volatilization be called, respectively, "stato-alembic," "dynamo-alembic," and "contact-alembic." To fit into the classification so far given, "stato-alembic metamorphism" must be rigorously distinguished from "stato-hydral metamorphism"; "dynamo-alembic metamorphism" from "dynamo-hydral metamorphism," and "contact-alembic metamorphism" from the purely thermal phase of contact metamorphism as the cause of new crystallizations. None of the three distinctions seems possible in practice. Nor has there been better success in attempting a workable dichotomous division of regional metamorphism and then contact metamorphism, each pair of subdivisions consisting of a class of rock changes induced by pure volatilization and a class induced by other causes, with or without volatilization.

In short, the inclusion of pure distillation in metamorphism seems inevitably to lead to excessive complication and to the abandonment of the effort to give strict definition to such established terms as "dynamic metamorphism," "static metamorphism," "load metamorphism," "local metamorphism," and "contact metamorphism." It is simpler to make new crystallization the criterion for metamorphism and to describe rock changes through pure volatilization by some such expression as *"alembic* (French, "alambic;" German, "Alembik") *transformation."*

FAVORED CLASSIFICATION IN ACTUAL PRACTICE

As far as possible, terms already in use have been preferred in building the classification. The violence done to existing definitions of the adjectives "regional," "dynamic," "static," and "contact" generally consists in lessening the intensiveness of each. The prevailing conflicts of definitions threaten to destroy these terms as practical aids in geology. To save them, no better course offers itself than to seek the factor common to the largest number of definitions for each of the words. With that common factor in supreme control of the definition, the word loses depth of meaning, but, as a rule, gains breadth and, above all, capacity for logical, clean-cut description and usage.

The four compound names—"stato-hydral," "stato-thermal," "dynamo-hydral," and "dynamo-thermal metamorphism"—are directly founded on root words already familiar and are mnemonically easy to locate in the scheme. They are, however, somewhat cumbrous and barbarous in form; synonyms of simpler make would, therefore, be welcome. The suggested equivalents, respectively, "hydro-," "load," "slaty," and "friction metamorphism" are arbitrarily defined from the standpoint of the literal meaning of each adjective. "Slaty" and "friction" have been adapted for the present purpose with some misgiving. The writer has not yet been able to find adjectives that might immediately suggest the ideas involved; more than usually in the proposed system, the technical names are here figurative rather than fully connotative. In practice the geologist seldom needs to distinguish under separate names "dynamo-hydral" and "dynamo-thermal" metamorphism.

The adjectives most likely to be useful in the future are "regional," "local," "static," "load," "dynamic," "contact," and "load-contact." The sanction of each of them is founded on theory of origins. General agreement in definition is bound to be indirectly proportional to the respective amounts of theory implied in these seven words. For the student of post-Cambrian rocks, the terms "regional metamorphism," "local metamorphism," "dynamic metamorphism," and "contact metamorphism" may be in constant use; "static metamorphism" is likely to be less in demand; "load metamorphism" and "load-contact metamorphism" are still less in active demand. For the student of the Precambrian complexes, all seven phases need expression, but he should feel the special need of "load metamorphism" and "load-contact metamorphism." Until the peculiar conditions of Precambrian time have been sensed and compared with later conditions, it is impossible to make a permanent definition of metamorphism or a universally acceptable classification of its phases.

The problem of metamorphism thus remains, where it has always been, chiefly in the hands of workers specializing in the Precambrian terranes. Intensive research on younger formations and laboratory experiment are both extremely valuable, but the field investigator of the Precambrian rocks must make his unique and first-rank contribution to the necessary sum of facts. To him especially the writer offers definitions and classification. In many instances the Precambrian specialist has gone into the field with too much reliance on single principles affecting rock alteration. He has overemphasized dynamic action, or the efficiency of vadose waters, or the purely thermal effects of burial, or the power of hot gases rising from the earth's interior. Preconceptions have thus too often prevented workers from observing critical facts in the field. Some of these geologists have preached false doctrines, not because they were too theoretical, but because they were too little theoretical and did not apply thoroughly the principle of multiple hypotheses. Scarcely one fundamental modern idea on metamorphism was not foreshadowed by writers in the heroic age of geology. Field men stumble, teachers are puzzled, and students are worried because the geological profession has not insisted on the maximum possible completeness of a systematic, rigorous classification of principles suggested long ago. Though but a report of progress and thus unfinished, such a classification serves as a means of expression and, yet more valuably, as a stimulus to further correct observation in nature.

The writer does not, of course, pretend to have formed definitions or classification which will satisfy geologists in general. He merely offers a scheme for criticism and *then improvement.* It may be pointed out that all names used in classification are either now represented in the leading languages of Europe or are capable of ready translation. The proposed scheme thus follows a peremptory rule in building a scientific system and specially invites international cooperation for its bettering.

Additional descriptive Terms

Since 1833 many words, other than those embodied in the present classification and yet denoting aspects of metamorphism, have been coined or adapted. Some have permanent value as aids to the description of metamorphic rocks, when the causes of their alteration are only partly known.

If one wishes to emphasize pressure as a leading physico-chemical condition in a given case, the term *pressure metamorphism* might be used. If so, the context should clearly indicate that its employment is due to a lack of knowledge as to the source of the pressure itself, whether primarily an incident of mountain-building or the effect of simple burial. If the choice between these alternatives is possible, then "dynamic metamorphism" or "load metamorphism," as the case may be, should be preferred.

The development of schistose structure in a rock is a stress phenomenon. That change might be called *stress metamorphism,* if the observer has not the data for assigning it to either static or dynamic metamorphism and yet wishes to contrast the type of recrystallization with that yielding a massive rock, such as common marble.

Properly guarded, *thermal metamorphism* might signify changes effected by high temperature. The use of this expression would, however, imply that the field observations do not suffice to make clear what is the source of heat—mere burial, dynamic action, or igneous intrusion. If water and high temperature had essentially cooperated, and again, if outcrops failed to show the source of heat, *hydrothermal metamorphism* might similarly be employed.

Katamorphism and *anamorphism,* denoting contrasted phases of rock alteration in general, seem likely to persist as useful descriptive terms. They represent a problem in the classification of processes which is quite different from the problem attacked in this paper, and the favored definitions of "metamorphism" and its subdivisions do not conflict with those of the two key words employed by Van Hise or Leith and Mead.

H. C. Sargent (1917, page 59) has proposed *"auto-metamorphism"* as a name for the intense decomposition of spilite, "due to retention of volatile constituents resulting from the physical environment of a submarine flow."

Finally, if a formation has been recrystallized more than once, it may be said to have undergone *superimposed metamorphisms,* or, more compactly, as suggested by Teall (1888, page 8), *superposed metamorphisms.* An adjective proposed by Koenigsberger (1910, page 670) suggests *polymetamorphism* as a synonym.

ULTRA-METAMORPHISM

Sederholm (1907, page 102) has called the complete remelting of a rock *anatexis.* With him one may describe anatexis as a phase of *"ultra-metamorphism"* (Holmquist, 1909) without running counter to the proposed definition of metamorphism. The course of the melting-up may be purely thermal or it may be hydrothermal. Sederholm (1907, page 102) makes the emanation of gases and heat from the general subcrustal region of the earth responsible for the *palingenesis* (rebirth) of Pre-cambrian granitic magma *in situ.*

Several French geologists, including Termier and Haug, still believe that the rise of hot gases from the earth's interior has generated the post-Cambrian batholiths from geosynclinal sediments. This extremely doubtful thesis regarding the geological efficiency of "colonnes filtrantes" is a matter relating to ultra-metamorphism rather than to metamorphism.

"Roches d'imbibition" result from contact metamorphism. They may graduate into complexes developed by lit-par-lit injection, which is commonly simultaneous with regional metamorphism and also a cause of contact metamorphism. But several considerations forbid belief that any voluminous granitic magma of post-Cambrian age has been at once cause and effect of gas-thermal alteration. On the other hand, conditions special to the earlier Precambrian may, as Sederholm suggests, have caused palingenesis in the older terranes, through the cooperation of heat and rising gases. In fact, there is some ground for the hypothesis that the earth's original crust was changed by load-contact metamorphism, palingenesis, and lit-par-lit injection *during* its original, slow formation. The geology of the Precambrian complexes seems to indicate for the original crust: (*a*) an average chemical composition like that of common granite; (*b*) a general gneissic structure, due to load metamorphism in the presence of abundant water and a steep thermal gradient; and (*c*) injection of countless granitic sills along the new planes of foliation, followed by more or less perfect load metamorphism of the sills themselves. A very thin surface shell of massive granitic or rhyolitic rock may have covered the thickening crust, but, below the depth of a few hundred meters, that crust would be a composite, as described. Perhaps Sederholm (1910, page 134) is right in assuming the possibility of actual representation of the original crust in the older Precambrian formations of Fennoscandia and Canada.

Certain pegmatites and perhaps certain veins of aplitic constitution may have been formed by the "selective solution" (Lane, 1913, page 704) of some components of a rock-mass which has undergone ordinary, though intense, metamorphism, dynamic or static.[4] Small bodies of such new magma, forced out of the parent formation and injected into other rocks, may cause a little contact metamorphism, but the magmatic bodies themselves are by-products of regional metamorphism and belong to the field of ultra-metamorphism.

According to the proposed definition, *exomorphic* changes, leading to new crystallizations near igneous contacts, must, as usual, be treated under metamorphism, while *endomorphic solution* of country rock is another example of ultra-metamorphism. Thus hybrid rocks properly fall in the igneous rather than the metamorphic class.

SUMMARY

The problem of rock alteration below the earth's shell of weathering is immeasurably complex. The kinds of change are many. The necessity of their indefinitely detailed discussion is one of the most insistent duties of a field geologist. Fruitful discussion depends on names and definitions. The most used and most important name is "metamorphism," the history of which shows a very notable failure of unanimity in usage. A review of the older definitions has led to one which is verbally new, but covering essential ideas underlying Lyell's use of "metamorphic," and is nearly the same as Harker's (1889, page 15) formal definition.

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[4] Since this paper went to press, Holmquist's 1916 article on the Swedish Archean has come to America. Holmquist (page 141) there clearly states his belief in the ultrametamorphic origin of many Archean pegmatites and aplites.

The expediency of that definition appears clearer after meanings have been properly assigned to such expressions as "regional," "local," "dynamic," "static," and "contact" metamorphism. Some of their respective published definitions can not be fully adopted without logical conflict with the preferred definition of metamorphism itself; yet the necessary departures from authority are, in general, not any more serious than if one tries to use these older terms in any other systematic, logical subdivision of metamorphic processes as now understood.

The existing terminology does not suffice to cover all the categories. Thus static metamorphism includes what are here called "stato-hydral metamorphism" or hydro-metamorphism, and "stato-thermal metamorphism" or load metamorphism. Dynamic metamorphism is divided into "dynamo-hydral metamorphism" and "dynamo-thermal metamorphism." Metamorphism of rocks, produced by their burial under overthrust masses, is called "dynamo-static metamorphism." Metamorphism by a combination of igneous injection and deep burial is distinguished as "load-contact metamorphism."

The question whether pure volatilization is technically a metamorphic process seems to be best answered in the negative.

How the proposed scheme may meet the needs of working geologists is a question briefly discussed. Those occupied with the Precambrian complexes are apt to find the expressions "load metamorphism" and "load-contact metamorphism" at least as useful as "regional metamorphism" or "dynamic metamorphism." The classification is fairly elaborate, but it will seldom be incumbent on the field investigator to consider the subdivisions of dynamic metamorphism or to apply the term "dynamo-static metamorphism." The memory must, however, be somewhat burdened in the use of any workable classification.

The suggested scheme does not interfere with the employment of certain descriptive words, which for various reasons have no place in it. Those appearing in the table of classification have been systematized in meaning, with a double object: first, to express the just conclusions of the present day as to genetic conditions; secondly, to furnish a scheme elastic enough to admit further discoveries about the origin of the crystalline schists, without seriously dislocating the partial classification so far erected.

The relation of metamorphism to "ultra-metamorphism" has been considered. Load metamorphism, load-contact metamorphism, and possibly the ultra-metamorphic processes of anatexis and palingenesis—all supplemented by dynamic metamorphism—appear to have been the principal phases under which the Precambrian rocks became crystalline schists.

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THE SILVER CITY QUARTZITES: A KANSAS METAMORPHIC AREA [1]

BY W. H. TWENHOFEL

(Presented before the Society December 27, 1916)

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INTRODUCTION

The Pennsylvanian section of Kansas and neighboring States is widely known for the essentially unaltered character of the composing sediments and the supposed absence of any effects referable to agents of igneous origin. The discovery, therefore, of evidence which proves that hydrothermal metamorphism has affected sands and sandy shales to the extent of changing them to quartzites is a fact of considerable interest and importance.[2]

The quartzites occur at Silver City,[3] the eastern end of a long east-west ridge in the southern part of Woodson County. This portion of the ridge forms the northeastern flank of a small anticline which for convenience may be given the name of the locality.

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[1] Manuscript received by the Secretary of the Society March 15, 1917.

[2] The metamorphic rocks were noted long ago by Hay and Mudge, and, as subsequently will be shown, the latter gave the correct explanation of the cause (see Trans. Kans. Acad. Sci., vols. vii and viii, 1881 and 1882).

[3] Silver City received its name from the supposed occurrence of silver there, and throughout the area in the map within the heavy line there are numerous old prospect pits, some of which are said to have attained depths exceeding 100 feet. In 1879 a

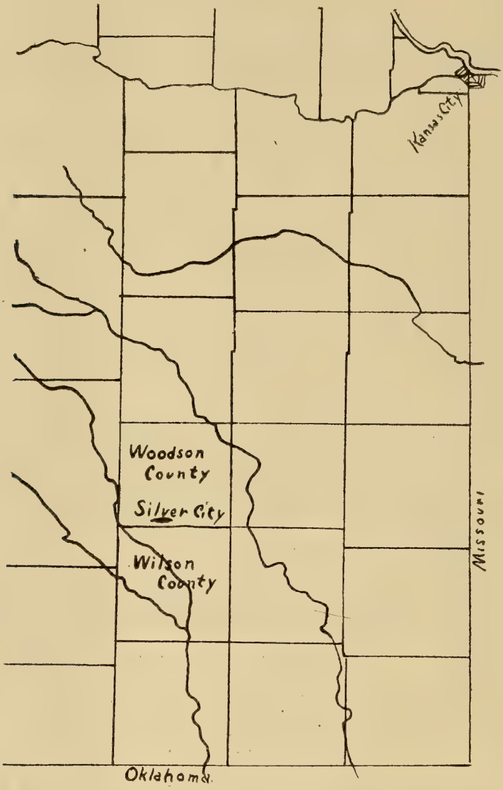

FIGURE 1.—*Index Map of the Locality of Silver City*

For assistance in mapping the structure and working out the geology the writer is indebted to two of his students, Messrs. Milburn Stryker and

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farmer drove into Yates Center, then the largest town of the region, and exhibited a piece of shining gray rock. The local authority pronounced it silver ore, and when the farmer stated that an entire hill of the substance existed a few miles to the south the exodus began, and within 24 hours the towns of Yates Center and Neosho Falls, the two important towns of the region at that time, are said to have been deserted by nearly the whole of their male population and a town of shacks and tents had been started on the hill of the supposed silver ore, and there soon followed all the accompaniments of a boom mining camp. There was intense and feverish activity until an assay of some of the "silver ore" was received from Kansas City, and it was learned that the supposed ore was merely worthless quartz. The miners "folded their tents and departed" and Silver City became a memory and a pasture, with nothing remaining to mark its onetime existence save the old prospect pits (compiled from newspaper reports).

W. L. Ainsworth. The work was done in the interest of the Fredonia Gas Company, through whose courtesy publication is permitted. In the preparation of the article the writer had the advantage of suggestion and criticism from Professors C. K. Leith and A. N. Winchell.

Geology of the Silver City Area

THE LOCAL SECTION

Before considering in detail the altered rocks it is thought best to give a brief description of the geology of the area surrounding Silver City ridge, in order to define the formations and to afford data for contrasting the altered rocks with the unchanged.

The local section includes two of the great sand-shale and two of the limestone members of the Kansas Coal Measures. In describing these divisions, the lithology normal to each is given, while the variations due to alteration are left to subsequent paragraphs. Only such details are given as have a bearing on the problem.

LAWRENCE SHALES

This, the topmost division of the local section, consists of red, yellow, gray, blue, and black shales and sandstones of ferruginous colors. The division is highly cross-laminated, of variable stratification and lithology in both the horizontal and vertical sense, and is generally of crumbling texture. Generally there are many bands of shale and sand which contain mica (apparently muscovite) in great abundance. The thickness is variable, but generally exceeds 150 feet. About 50 feet remain on the east tip of Silver City ridge.

IATAN (KICKAPOO) LIMESTONE[4]

This division is one of the most easily recognized of the Kansas Coal Measures and, for a thin member, its horizontal extent is remarkable. The upper layer is a compact, very dark blue, semicrystalline limestone of fine texture and brittle fracture. The farmers describe it as flinty. It is characterized by a highly developed vertical jointing, with the joint planes meeting at oblique angles. The thickness of this layer varies between 1 and 2 feet. Below the upper layer are from 2 to 10 feet of strata of variable lithology with those of limestone composed for the most part of the tests of *Fusulina.* Near Silver City the thickness of the whole is about 12 feet.

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[4] The name "Iatan" was applied to this limestone by Keyes, Am. Geologist, vol. 23, 1899, p. 306. Subsequently Haworth and Bennett (Kansas University Geol. Surv., vol. ix, 1908, p. 105) proposed the name of "Kickapoo." Since the former has priority, it is here used.

LE ROY SHALES

These are of a lithology and stratification equally as variable as are the Lawrence shales, but in the Silver City area they are of a lighter color; red shades are not common, while yellows predominate. Far less sand is also present and the greater portion of the division is a shale. Small flakes of mica are quite common. At the base are about 80 feet of dark blue and black shales. The division is known to be 204 feet thick on the northwestern margin of the area.

STANTON LIMESTONES

These are the lowest rocks exposed in the immediate vicinity of Silver City. They are gray, rusty spotted limestones of variable thickness and are not well bedded. They are not exposed in the altered area.

THE SILVER CITY ANTICLINE

The Silver City anticline has the form of an elliptical dome with the long axis trending nearly east and west. Due to lack of data, the eastern margin is perhaps not quite correctly mapped. The other portions of the structure are believed to be fairly accurately drawn. With the exception of the northeastern margin, all margins are fairly regular. The former is comparatively irregular, and it is clear that in the development of the anticline considerable crushing and fracturing occurred there. There is no evidence of faulting. On the contrary, the outcrops of the strata show the improbability of the presence of a fault with a throw of more than 4 or 5 feet. The anticline is expressed in the topography as a basin.

DETAILED GEOLOGY OF SILVER CITY RIDGE

The Lawrence shales and sandstones, which on the adjacent ridges as well as on the north side of Silver City ridge have the characteristics typical of the division, consist throughout the area in the map within the heavy line of very hard, compact quartzites, which locally contain small cavities lined with crystals of quartz and, more rarely, of pyrite. There is no trace of the red colors which are characteristic of the rocks of this division in surrounding areas, but instead there are shining gray and greenish shades. In the sunlight the quartzite sparkles brilliantly, and it was probably this characteristic which led to its being mistaken for silver ore. Examination of the rock in thin-sections proves it to be composed of grains of pure quartz sand cemented with quartz with a variable proportion of chlorite in those portions which are of greenish shades. Beds of the latter shades are generally finely laminated and originally probably contained some argillaceous and ferruginous material. The lamination is original, being due to conditions of sedimentation and not to parallel development of minerals induced by the pressure.

The upper layer of the Iatan limestone at the point A is of the normal character and continues so to the point B. Just east of B the cracks in the limestone are filled with hard black chert, which within a distance of a hundred or so feet to the east completely takes the place of the limestone, the change being gradual. The strata are well exposed, so that no mistake of identity is possible. The change is also accompanied by a thickening of the bed, an increasing percentage of impurity therein, and the assumption of a greenish shade. Fossils are visible in the replaced rock. A thin-section made from the chert filling the cracks in the limestone shows nothing other than would be expected in such a rock. A section from the equivalent of the limestone east of B shows the development of a considerable amount of chlorite. At C there is no trace of the limestone, but what appears to be its stratigraphic position is held by a

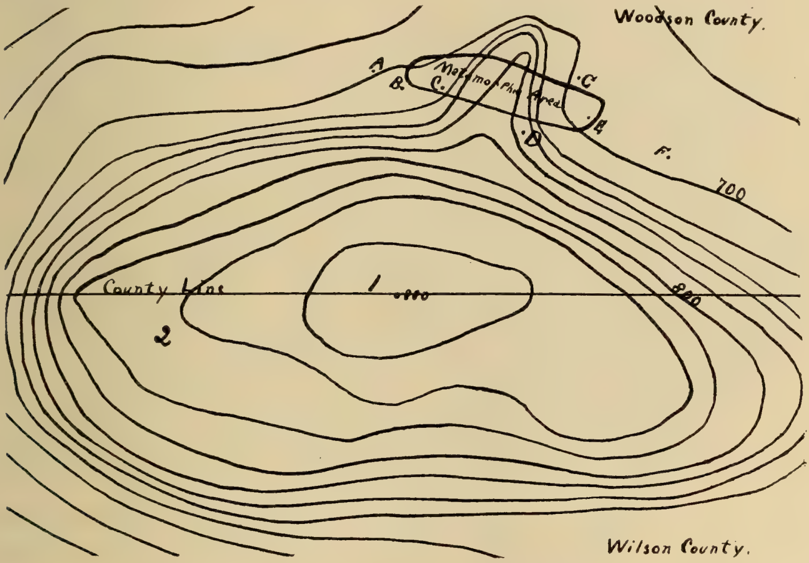

FIGURE 2.—*The Silver City Anticline*

Elevations are based on an assumed elevation of 1,000 feet. The area within the heavy line is underlain by the altered rocks brecciated, dark green, very earthy chert, which has a thickness of about 5 feet. The bed could not be traced from B to C, as the interval is covered; but the character of the rock, except for the brecciation, is the same, and there seems little doubt but that the correlation is correct. A thin-section made from the breccia at C showed exactly the same mineral constituents as the rock in the place where brecciation had not occurred. The cherty fragments show no wear whatever and are generally, but not everywhere, well cemented together, the cement being of a lighter shade of green, but still dark. Many of the fragments have their peripheral portions nearly white, or at least of a lighter shade than are the centers, and in the cases of many of the smaller pieces the change of color extends to the center. At D typical Iatan limestone occurs, while at E the degree of brecciation is greater than was seen elsewhere, although, as in the previous instance, it is not certain that the breccia is the equivalent of the limestone, although it holds what appears to be the position belonging to the latter, and in it was found a marine fossil which could not have come from either of the shale divisions, since they are without marine fossils in this region. Mineralogically, the breccia at E is somewhat different from what it is at C, as is shown by the notes which Professor Winchell kindly made for the writer. At G typical Iatan limestone is exposed, and traced northwesterly it shows no change. At F the alteration appears to be merely initial, while east of F there are no exposures in which any evidence of alteration is visible. In none of the exposures of this division was there observed any parallel arrangement of minerals or rock fragments.

The Le Roy shales underlying Silver City ridge are finely laminated, well cemented, fine-grained quartzites of a gray to greenish color. There are no yellows or reds, nor is there any orientation of constituents which is referable to dynamic processes. In the deepest shaft which was dug Professor Mudge states[5] that the sandstones "assumed the form of bluish green cherts" which "is traversed by veins of white quartz." Hay considered this chert to be a "true igneous rock,"[6] a view not supported by Mudge. The shafts are now largely filled up, but much of the debris which was thrown from them remains scattered over the ridge, and this debris contains no igneous rocks.

Near the top of the south side of the ridge are several very excellent cold-water springs. Since they occur on that side of the ridge from which the strata are inclined, it is rather difficult to explain their presence except on the assumption that the water rises along fractures.

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[5] Mudge: Trans. Kansas Acad. Sci., vol. vii, 1881, p. 12.

[6] Robert Hay: Ibidem, vol. viii, 1882, p. 17.

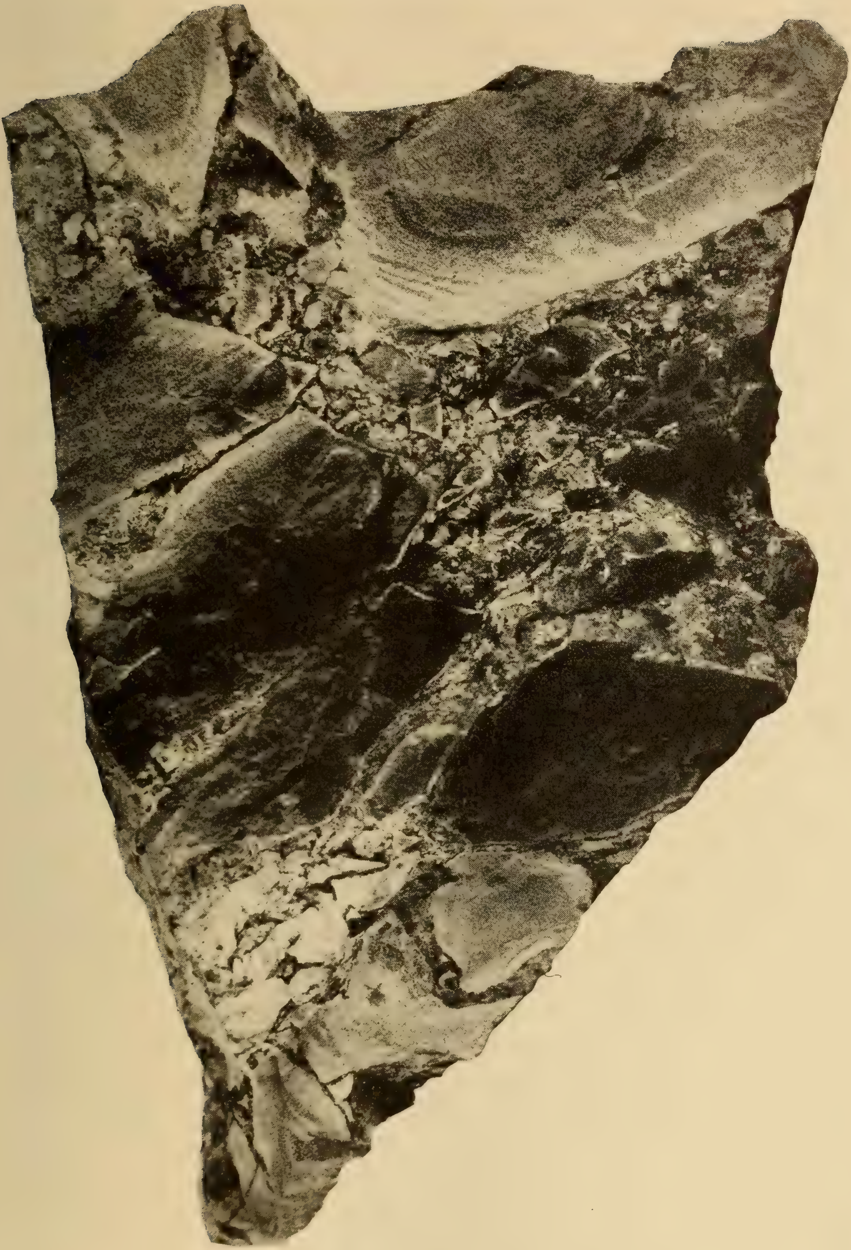

FIGURE 3.—*The Silver City Breccia (natural size)*

The large fragments are composed of chert and chlorite with rare hornblende and epidote. The matrix consists chiefly of acicular dark green hornblende

The notes which follow were kindly prepared for the writer by Prof. A. N. Winchell. Specimen number 4 came from the brecciated equivalent of the Iatan limestone of locality E, while number 7 was derived from an exposure of the Le Roy shales near the point D.

"Number 4. In hand sample the rock is composed of angular fragments of dark green color which have been altered in part (by surface waters?) to a white mineral. These fragments are held together by a heterogeneous cement which includes some material probably detrital in origin and some which has crystallized from solution. The latter is chiefly acicular dark green hornblende in rosettes.

"In thin-section the dark green color of the fragments is found to be due to abundant well crystallized lamellæ and needles of dark green chlorite, while the white mineral is chiefly opal or chert. There is also some rare hornblende and rather common grains of epidote which form granular aggregates in some places. The epidote is not only pleochroic, but also varies in color in different crystals from golden yellow to brown and brownish gray. It is biaxial, has high relief and extreme birefringence, indicating an epidote rich in iron.

"The probable history of the rock is as follows: A siliceous limestone was broken by local movements into abundant fragments of all sizes. The broken zone furnished a ready channel of flow for carbonated waters which dissolved and removed the iron and carbonates from the smaller fragments and from the outer zone of the larger fragments, thus increasing the porosity of the mass. At a later date the same channels served as paths of escape for hot solutions coming from greater depths, and these removed any remaining carbonate and at the same time caused the growth of chlorite, epidote, and hornblende. Such solutions were probably wholly or partly of igneous origin.

"Number 7. In hand sample the rock has a light grayish green color with very minute brightly reflecting white scales. It weathers to a darker brownish green color.

"In thin-section the texture is intermediate between that of a pelite and that of a psammite, the pelite ground-mass being plentifully sprinkled with rounded grains of feldspar. The chief constituents are orthoclase and finely divided argillaceous material, including chlorite, sericite, and kaolin. There are rare crystals and fragments of zircon, apatite, and magnetite. Recrystallization has developed a mineral of hazy grayish brown to brownish green color having high relief and strong birefringence; it is biaxial and negative with a large optic angle and a granular habit; it is almost certainly epidote."

Two wells have been drilled on the Silver City anticline, the places being indicated on the map as 1 and 2. Each reached the Mississippian limestone at depths a little greater than 1,300 feet. In the well of location 1 the drillers constantly complained that they were not finding rocks with which they were familiar and which they had found in the wells of the vicinity. When the well of location 1 proved a failure, location 2 was chosen in order to get as far as possible from the altered rock of Silver City ridge. In this well the rocks did not materially differ from those of well number 1, except that the abnormal rocks were met at a slightly greater depth.

Neither the logs of the wells nor the samples therefrom showed igneous rocks, but many horizons of slate were indicated. The rocks which drillers indicate as slate, however, are generally hard shales, and such is probably the case in these wells, as the logs also show shales lying between slates. In each well rocks were encountered which the drillers identified as mica. These proved to be merely fine-grained sandy shales carrying large quantities of hydrated mica. Black limestones were indicated in the logs. These were found to contain no calcium carbonate, but to be hardened chloritized material containing hydrated mica. They appear to have been black shales. Both the micaceous substances and the black rocks have a distinctly soapy feel.

The data given by the well logs make it appear quite probable that alteration has affected the sediments beneath the anticline to a considerable extent, and that the alteration becomes deeper with distance from the Silver City ridge. In itself, however, the evidence of the wells is of little value; but taken in connection with the actual fact of alteration it is corroborative.

Summary of the Data

(1) Silver City ridge lies on the northeastern flank of a comparatively high anticline, and on this flank there has been rather decided local deformation of the strata.

(2) In a narrow zone on the northeastern flank of the anticline the Lawrence shales, which elsewhere are poorly cemented sands and shales of varied colors, are compact, hard quartzites of a gray or greenish color, the green being due to the development of variable proportions of chlorite.

(3) The Iatan limestone, which elsewhere than on the south face of Silver City ridge is a compact splintery limestone in its upper division, is there replaced by a dark green earthy chert, or a breccia from the same, with the chert making its first appearance in a purer and harder form. as fillings in the cracks of the limestone, while the matrix of the breccia and, to a lesser degree, the fragments contain hornblende, epidote, and chlorite which crystallized from solution at a time subsequent to the brecciation.

(4) The Le Roy shales, which in the areas surrounding Silver City ridge are poorly cemented yellow and gray sandy shales, on the south side of the ridge are fine-grained, well laminated, firmly cemented gray and light green quartzites.

(5) Not one of the altered rocks has had developed any parallel orientation of its minerals or any structure which can be referred to dynamic metamorphism.

CAUSES OF THE ALTERATION

It is quite possible for quartzite to be developed through processes of ordinary cementation of sedimentary rocks. No special conditions are required for the development of chert and flint, since these are known to be commonly formed in the zone of fracture in the presence of cold water. The occurrence of these rocks, therefore, requires nothing other than ordinary sedimentary and ground-water conditions. No known process of sedimentation, however, can account for the development of the hornblende and its origin must be referred to some other process, and as the chert and quartzite appear to be genetically related to the hornblende, it is inferred that all three, together with the chlorite and the epidote, originated in the same manner.

It has been pointed out that there is no parallel development of minerals in any of the rocks, so that pressure metamorphism as a cause of the alteration is eliminated. Metamorphism of the contact type appears to be out of question, as no igneous rocks have been recognized in the strata altered or contiguous thereto. Furthermore, the alteration is quite unlike that generally associated with heat metamorphism. This leaves hydrothermal metamorphism as the only possible cause of the alteration, and everything which was observed is in harmony with the view that the quartzites and associated rocks were developed through the circulation of hot waters. Mudge explained the metamorphism in the same manner.[7] He, however, failed to observe the hornblende, epidote, and chlorite.

The sequence of events in the Silver City area is believed to have been something as follows: Prior to the deformation of the strata a quite normal lithology of the three divisions known to have been modified obtained in the Silver City area. Deformation locally brecciated the upper Iatan limestone—the only brittle member of the known modified rocks—and opened cracks to greater depths. Circulating waters which were probably of surface origin removed the soluble constituents from the fragments of the limestone, leaving the clay and silica with perhaps some increase of the latter. Later, hot solutions coming from great depths circulated through the fractured and porous zones and ultimately filled the pores and cracks with chert, hornblende, chlorite, and epidote and cemented the fragments together with substances of the same character. The sandstones and shales were also firmly cemented through the precipitation of material from these hot solutions, the cementation being accompanied by the development of chlorite. Nothing is known as to the depth from which the hot water came or its method of origin.

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[7] Mudge: Loc. cited, p. 12.

RELATION OF THE ALTERED ROCKS TO THE LEAD AND ZINC DEPOSITS OF SOUTHEASTERN KANSAS, THE ROSE BOULDERS, AND THE GRANITES REPORTED FROM THE DEEP WELLS OF CENTRAL KANSAS

The recognition of the fact that Pennsylvanian strata of eastern Kansas have been altered by hydrothermal processes raises three questions. They are as follows: (*a*) Is there any relation between the metamorphism which has occurred at Silver City and the lead and zinc ores which are found in the near vicinity?[8] (*b*) Does the fact of alteration have any bearing on the origin of the granite porphyry boulders which occur in the vicinity of Rose, only about 6 miles to the north?[9] (*c*) Is there any connection between the granite reported in deep wells of central Kansas and the metamorphism at Silver City? These three questions will be considered in detail.

(*a*) No lead or zinc minerals have ever been noted in the altered rocks of Silver City, so that it is quite unlikely that the formation of the quartzites and related rocks are related to the development of the lead and zinc deposits.

(*b*) While studying the boulders at Rose, the writer tested as one hypothesis of origin the possibility that they might have been derived from a dike, sheet, or flow. It was pointed out that a small quartz vein had been observed a distance of a quarter of a mile from the boulders, and it was stated that the alignment of the greater portion of the material is in harmony with the idea that the boulders are parts of an extrusion or intrusion; but the coarse-grained character of the material, the absence of metamorphism and contiguous deformation caused the hypothesis to be rejected. Since that paper was written the writer's attention has been called to the fact that three wells have been drilled on the southeastern margin of the area over which the boulders are distributed, each reaching the Mississippian limestone. No alteration of strata is reported to have been found in the wells, nor was any igneous rock encountered. One of the wells is said to have produced gas for several years. The evidence of the wells supports the view that there is no intrusion or extrusion present at Rose, and, if this view be correct, it follows that the boulders bear no relation to the metamorphism observed at Silver City.

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[8] Haworth: Kansas Univ. Geol. Surv., vol. viii, 1904, p. 43.

[9] Twenhofel: Am. Jour. Sci., 1917, p. 363.

(*c*) Facts which have lately come to the writer from many sources indicate that in central Kansas real granitic masses in place are being reached by the drill. All the evidence, however, which the writer has received indicates that the granites are older than the overlying Pennsylvanian strata. If such be correct, it follows that they bear no relation to the metamorphism observed at Silver City. If they be intrusive in the Pennsylvanian strata, there may be some connection.

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ORIGIN OF DOLOMITE AS DISCLOSED BY STAINS AND OTHER METHODS [1]

BY EDWARD STEIDTMANN

(Presented before the Society December 28, 1916)

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[1] Manuscript received by the Secretary of the Society January 25, 1917.

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INTRODUCTION

THE BASES FOR INFERENCES

Direct observations on the process of dolomitization are all but lacking. Its limiting conditions have not been found by experiments. Field and petrographic facts, therefore, are at present the best bases from which inferences as to its nature may be attempted.

Thus far most studies on the origin of dolomite have been based on (1) published field and petrographic facts of a general nature which were not collected with the specific aim of throwing light on the dolomite question, and (2) generalizations which grew out of the general field and petrographic facts just alluded to. To this type of inquiry into the origin of dolomite the writer[2] contributed in 1911. He is now convinced that progress on the dolomite problem will be made chiefly by direct studies of dolomites themselves. This paper presents the principal results of his first attempt by the direct method.

A perplexing difficulty involved in the method of direct attack is to know what to look for in dolomites and to know how to evaluate the bearing of observed facts on the question of dolomite genesis. This difficulty will no doubt be less felt when more direct studies like those of Skeats and others have been made. Even now the application of the direct method promises great rewards.

AIM AND METHOD OF STUDY

This paper aims to present a few direct observations on dolomites and their bearing on the time, manner, and conditions of dolomitization. It is based on a study of specimens and slides in the collections at the University of Wisconsin, but mainly on studies of the Paleozoic rocks of Wisconsin. The writer is indebted to W. O. Hotchkiss, State Geologist of

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[2] E. Steidtmann: Evolution of limestone and dolomite, Jour. of Geol., 1911.

Wisconsin, for opportunities of investigation. The method followed most intensely was that of differentiating calcite and dolomites by stains. In the field were noted the relations of dolomite to limestone beds, the textures and structures of dolomite, and the characteristics of its fossils, while in the laboratory the relations of calcite and dolomite grains to the bedding, pervious structures, and to fossils were examined in thin-sections and on polished slabs with the aid of stains.

Staining methods for distinguishing calcite and dolomite, although described in petrographic texts, are not in common use, because they are generally thought to involve too painstaking a technique to reward the effort. Contrary to his expectations, the writer found them easy to manipulate after experience suggested certain modifications, and so interesting that a statement regarding their nature and efficacy seems justified.

PRINCIPLES UNDERLYING CALCITE AND DOLOMITE STAINS

The efficacy of stains for distinguishing calcite and dolomite is based on two facts. (1) Calcite has different chemical properties than dolomite. Certain reagents which react with dolomite either do not react with calcite or else react at a different rate. (2) Complete mineral gradations between calcite and dolomite are lacking. If isomorphism between the two minerals was complete, staining capacity would not be a sharp index of composition.

FACTS SHOWING THE LACK OF COMPLETE ISOMORPHISM BETWEEN CALCITE AND DOLOMITE

The MgO[3] content of calcite crystals rarely exceeds 2 per cent. In dolomite crystals CaO is nearly constant, but MgO is commonly replaced by small amounts of FeO or of FeO and MnO. The FeO limit is about 10 per cent, but is rarely reached, it seems, excepting in Precambrian sediments and in vein deposits. Modern organic calcium carbonate secretions, although crystalline, often show a high $MgCO_3$ content. Calcitic echinoderm[4] skeletons from tropical seas are known to contain up to 13 per cent $MgCO_3$, apparently in isomorphous union with calcite. Thin-sections of *Isocrinus*[5] *decorus* off Havana, Cuba, with 11.42 per cent $MgCO_3$, examined by the writer reacted homogeneously to stains and acids as calcite.

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[3] For analyses see Doelter's Handbuch der Mineralchemie, Bd. i, 2, p. 276, and Bd. i, 3, pp. 360-383.

[4] U. S. Geol. Survey, Prof. Paper 90-D, p. 34.

[5] Specimens obtained through the courtesy of Austin H. Clark, National Museum, Washington, D. C.

Skeats describes thin-sections of some Tertiary[6] coral reef materials containing as much as 15 per cent $MgCO_3$, but no dolomite.

To what extent[7] organic secretions of older rocks contain MgO-bearing calcite has not been thoroughly studied. Paleozoic limestones and dolomites examined by the writer never showed any marked difference between the proportions of calcite and dolomite differentiated by stains and the proportions computed from chemical analyses. If notable amounts of $MgCO_3$ had been in isomorphous union with calcite, stains ought to have shown a deficiency of dolomite.

METHODS OF DIFFERENTIATING CALCITE AND DOLOMITE BY STAINS

The thin-sections and polished slabs of limestones and dolomites, in which the calcite and dolomite grains are to be differentiated by staining, may be etched first in dilute acid, in order to bring the two minerals in relief. With polished slabs, the etching process can be watched closely and stopped as soon as relief has become prominent. In some cases etching alone is sufficient to differentiate calcite from dolomite. For example, dolomite rhombohedrons, when embedded in a compact calcite groundmass, are brought into conspicuous relief. However, when a limestone or dolomite is not uniform in texture and porosity, etching produces relief even when the rock contains only one mineral.

Thin-sections of limestones or dolomites which are to be stained should be made without the cover-glass. Their preliminary etching can be accomplished by a momentary immersion in very dilute HCl, followed by washing in water to stop further corrosion.

Calcite can be stained violet by immersion for two minutes in a modified form of the Lemberg solution. The stain, if applied as outlined farther on, is a reliable indicator of calcite and is not affected by size of grain, porosity, or other physical conditions. If it is desired to stain both dolomite and calcite, the dolomite can be stained first by immersing the sample in a dilute solution of HCl—1 part concentrated HCl to about 100 parts of water, to which a few drops of freshly prepared potassium ferricyanide have been added. In every one of several hundred samples treated in this way by the writer dolomite turned blue, while sedimentary calcite remained unaffected. Some vein calcites also showed a faint reaction. The blue reaction of the dolomite is, of course, due to its FeO content.

The results were so consistent for the samples studied that it may fairly raise the question, How general is the FeO content of dolomite and the lack of FeO in sedimentary calcite? The additional evidence of analyses presented later suggest that these conditions are the rule.

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[6] E. W. Skeats: Bull. Mus. Comp. Zool., vol. 42, 1903.

[7] U. S. Geol. Survey, Prof. Paper 90-D, p. 37.

PREPARATION OF LEMBERG STAIN

The standard Lemberg solution is prepared by boiling for 20 minutes a mixture of 4 grams $AlCl_3$, 6 grams extract of logwood, and 60 grams of water, with constant stirring and addition of water to make up for loss by evaporation. It is then filtered and bottled for use. Calcite, when immersed in it, becomes coated with $Al(OH)_3$, which absorbs the dye and acts as a mordant. Dolomite is coated in about 30 minutes. When prepared in this way with fresh $AlCl_3$ crystals, it coated calcite almost instantly with a thick blue gum blistered with carbon dioxide bubbles. When washed the gum peeled off, and on drying it cracked. The standard preparation diluted with 1,200 cc. of water gave perfect results.

Time of Dolomitization

TWO HYPOTHESES

Two hypotheses regarding the time at which a dolomite developed can be formulated. (*a*) It may have developed in the sea as a sediment either by direct precipitation or by reactions within the limy sediments of the sea-bottom. (*b*) It may have been formed by the replacement of limestones through the action of waters underground after the limestones had emerged from the sea. It is also conceivable that the dolomitization of a formation began in the sea and was carried farther in post-emergent times. Evidence as to the time of dolomitization in specific cases is sometimes difficult to obtain.

POST-EMERGENT DOLOMITES

Proof that some dolomite masses are post-emergent in their time of development lies in the fact that they replace limestones adjacent to faults and fissures. Well known cases of this kind are found in the Joplin zinc district and at Aspen, Colorado. Dolomite vein materials also belong to this class. Small deposits of the latter are found in almost any dolomite quarry of the Central States. Although common, the dolomites developed under emergent conditions seem to include only a minor portion of dolomite deposits.

PRE-EMERGENT DOLOMITES

Evidence from stains and other methods of direct study.—That the majority of dolomites were formed as marine sediments is shown by the following facts:

1. Stains show that sediments composed of mixtures of calcite and dolomite are subordinate in abundance to pure or nearly pure limestones and dolomites. Analyses show this also (see diagram, figure 1). Primary calcite is rare in dolomites; conversely, dolomite crystals are uncommon in limestones. Primary calcite, as distinguished from vein or secondary calcite, is characterized by gray color, numerous minute inclusions, and low degree of transparency in thin-sections. In all samples studied by the writer it contained no FeO. No primary calcite was found in the Niagara, Lower Magnesian, and the Galena-Trenton formations excepting the transition beds between the latter in western Wisconsin. The small excess of $CaCO_3$ over dolomite requirements was in the form of clear vein calcite, in all formations lacking primary calcite. Complete gradations from limestone to dolomite ought to be common if dolomitization were caused chiefly by underground waters.

2. Not uncommonly calcitic casts are embedded in dolomite, and hollow casts are often inclosed by perfect molds of dolomite (see plate 22, figure 1). Either the casts were embedded in a matrix of dolomite and then in some cases dissolved out after the rock was rigid enough to preserve openings, or else the matrix only was dolomitized by underground water after consolidation. The latter seems less probable. After the matrix had set it seems that it would have been replaced no more readily than the casts.

3. The compact glasslike, fine-grained limestone beds at the base of the Galena formation of southwestern Wisconsin inclose many minute dolomite rhombohedra (see plates 24 and 25). They appear to have been embedded in the calcite before consolidation. The rock at present seems nearly impervious. If formed by underground waters when the rock was in its present state, their development was effected without the slightest sign of volume change. In the Cœur d'Alene district very active ore-bearing waters have replaced quartzite by siderite without volume change, but these replacements are related to fissures. The dolomite grains in question are not so related; hence it is quite certain that they formed in the sea before the rock solidified.

Published facts indicating the marine origin of the majority of dolomites.—1. The distribution of most dolomites is related to stratigraphic planes and not to secondary structures such as faults and fissures. Alternations of limestone and dolomite beds and formations are not uncommon. More, however, ought to be known on the distribution of dolomite formations with respect to stratigraphic horizons. It is still impossible to decide in many cases whether a dolomite in one region grades into a contemporary limestone in another. Unsettled correlations and the fact that many geologic reports call dolomites limestones handicap study along this line.

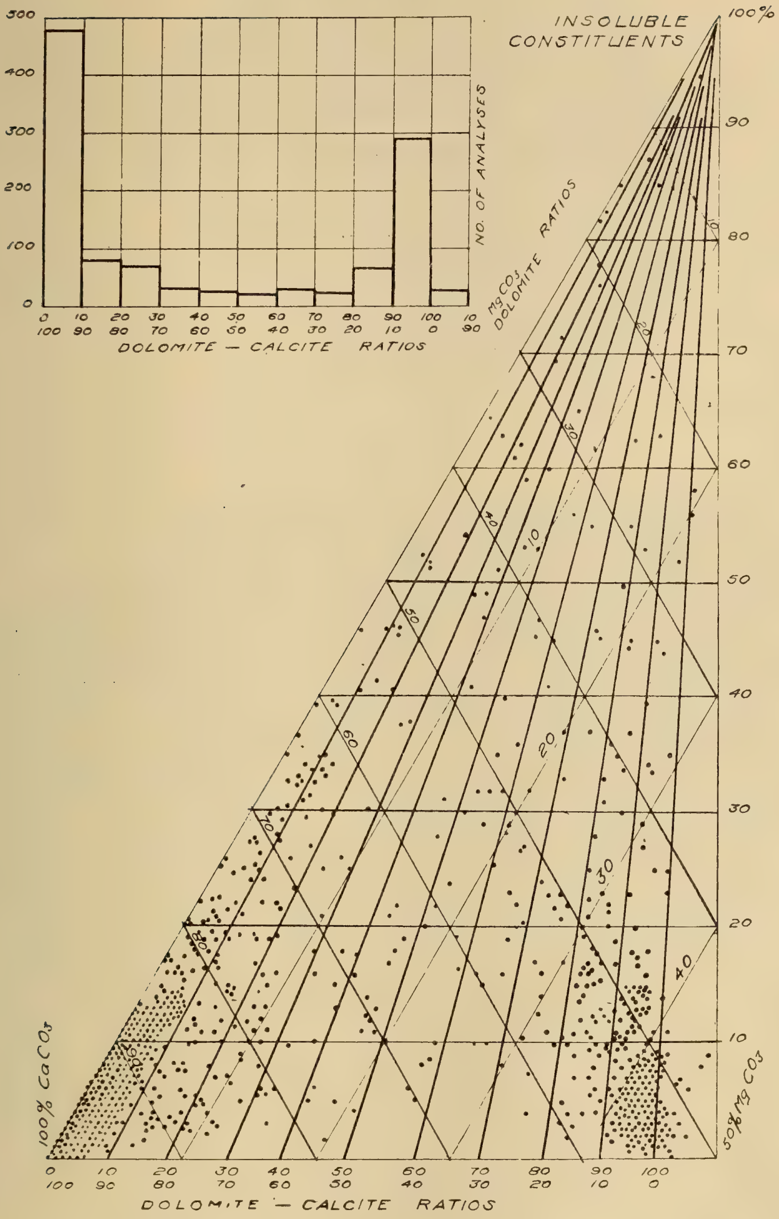

FIGURE 1.—*Graphic Representation of Analyses of Limestones and Dolomites*

The diagram is made up from 1,148 analyses of specimens from all over the United States, of which 988 were compiled by Ries, in New York Museum Bulletin 44, 1901. In the triangle each dot stands for an analysis. The percentage of each constituent of an analysis is determined by the distance of the dot representing the analysis from the corner, which represents 100 per cent of the respective constituent. The 100 per cent $MgCO_3$ corner is not shown, as none of the analyses showed more than 50 per cent $MgCO_3$. The diagram shows that nearly pure limestones and dolomites are much more common than mixtures of the two, and that the mixed beds average higher in insoluble constituents than the pure limestones and dolomites.

2. The pore space of the unfolded Mississippi Valley dolomites ranges from a fraction of 1 per cent to 13 per cent or more. The limestones of this region have about the same range of porosity (see tables 1 and 2). If dolomitization by underground waters were a very general process, one would expect limestones to have preserved their composition by virtue of a low degree of permeability.

TABLE 1.—*Porosity of Dolomite building Stones*

Formation	Age	Locality	Determined by	Per cent of pore space
Lower Magnesial	Ordovician	Bridgeport, Wis.	E. R. Buckley[8]	13.19
Trenton	Ordovician	Duck Creek, Wis.	E. R. Buckley	1.04
Niagara	Silurian	Wauwautosa, Wis.	E. R. Buckley	6.40
Niagara	Silurian	Genesee, Wis.	E. R. Buckley	1.12
Niagara	Silurian	Lannon, Wis.	E. R. Buckley	3.17
Niagara	Silurian	Burlington, Wis.	E. R. Buckley	8.32
Niagara	Silurian	Knowles, Wis.	E. R. Buckley	4.43
Niagara	Silurian	Marblehead, Wis.	E. R. Buckley	.77
Niagara	Silurian	Sturgeon Bay, Wis.	E. R. Buckley	.43
	Cambro-Ordovician	De Soto, Mo.	H. A. Buehler[9]	6.717
	Cambro-Ordovician	Jefferson City, Mo.	H. A. Buehler	8.574
	Cambro-Ordovician	Koeltztown, Mo.	H. A. Buehler	9.99
	Cambro-Ordovician	Jefferson City, Mo.	H. A. Buehler	9.24
	Cambro-Ordovician	Rolla, Mo.	H. A. Buehler	13.00
	Ordovician-Silurian	Bowling Green	H. A. Buehler	10.62
	Mississippian	Sedalia	H. A. Buehler	13.38
	Ordovician	Big Horn Mts.	W. J. Mead[10]	1.31

TABLE 2.—*Porosity of Limestone building Stones*

Formation	Age	Locality	Determined by	Per cent of pore space
	Ordovician-Silurian	Jackson, Mo.	H. A. Buehler[11]	.32
	Ordovician-Silurian	Carthage, Mo.	H. A. Buehler	1.34
	Mississippian	Columbia, Mo.	H. A. Buehler	3.104
	Mississippian	Hannibal, Mo.	H. A. Buehler	5.031
	Mississippian	Joplin, Mo.	H. A. Buehler	1.129
	Mississippian	Noel, Mo.	H. A. Buehler	.85
	Mississippian	Pierce City, Mo.	H. A. Buehler	1.239
	Mississippian	Phœnix, Mo.	H. A. Buehler	1.939
	Mississippian	St. Louis, Mo.	H. A. Buehler	7.30
	Mississippian	Springfield, Mo.	H. A. Buehler	.92
	Pennsylvanian	Breckinridge	H. A. Buehler	8.185
	Pennsylvanian	Kansas City, Mo.	H. A. Buehler	9.148
	Pennsylvanian	Princeton, Mo.	H. A. Buehler	10.04 4.92
Bedford	Mississippian	Bedford, Ind.	Blatchley[12]	7–14.

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[8] E. R. Buckley: Building stones of Wisconsin. Bull. 4, Wisconsin Geol. Survey.

[9] Vol. ii, 2d series. Missouri Bureau of Geology and Mines.

[10] Bull. Geol. Soc. Am., vol. 24, 1913, p. 621.

[11] Vol. ii, 2d series. Missouri Bureau of Geology and Mines.

[12] 1st Ann. Rept. on Geology and Natural Resources of Indiana.

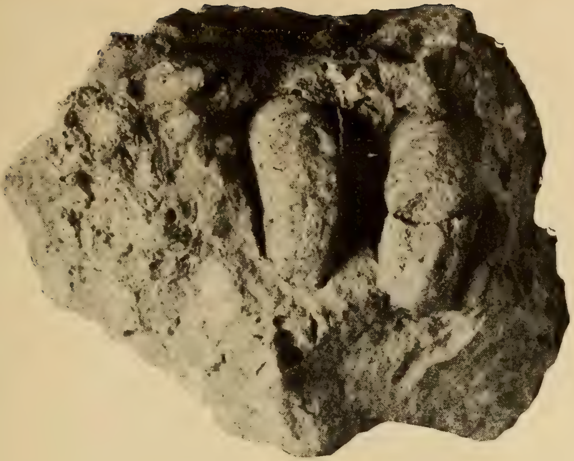


FIGURE 1.—HOLLOW GASTROPOD CAST INCLOSED BY PERFECT DOLOMITE MOLDS
From Trenton, near Beloit, Wisconsin

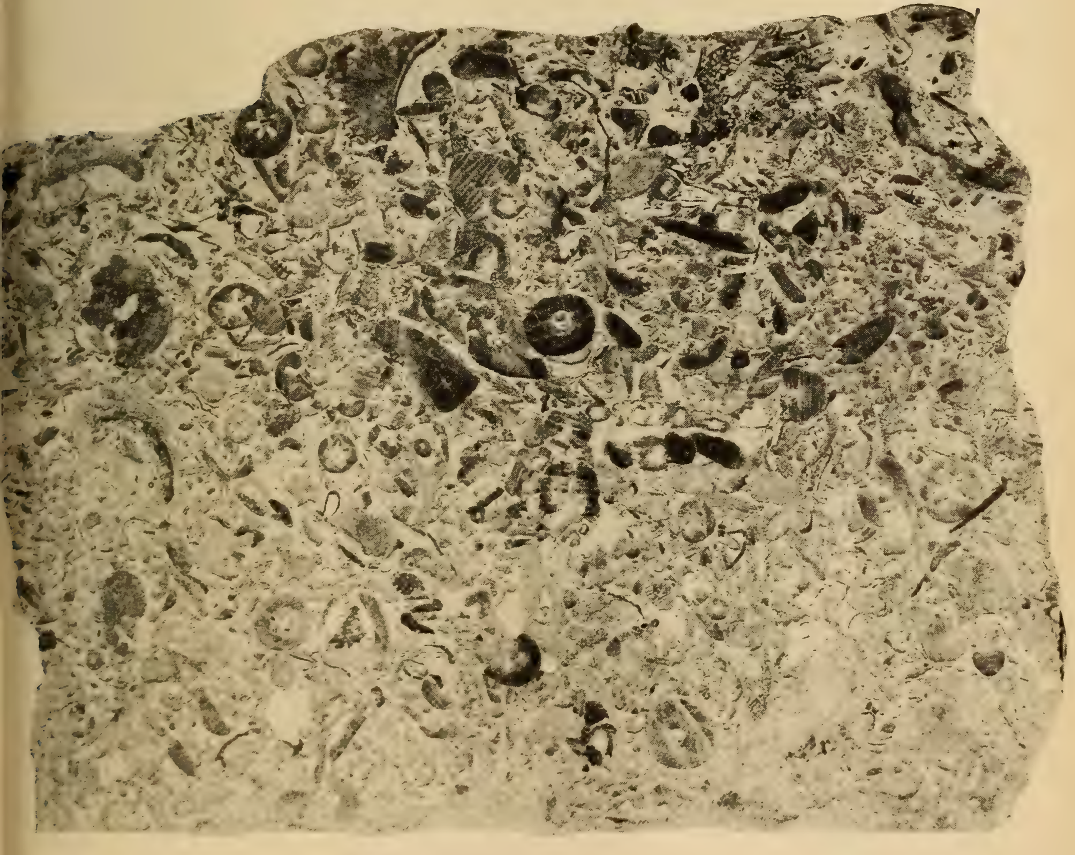
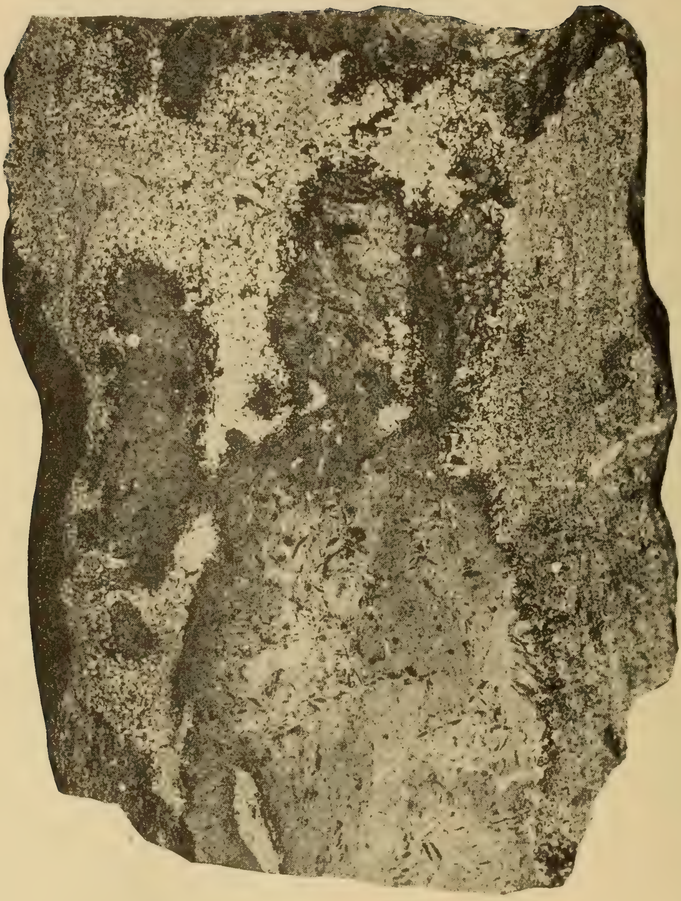


FIGURE 2.—PERFECT CALCITIC CASTS
The casts are embedded in fine-grained dolomite, the white unstained areas of the picture. Dolomite also fills the shell cavities. Natural size. From Trenton; locality uncertain

CALCITE CASTS



SECTION OF DOLOMITE FROM LANCASTER, WISCONSIN

This section, of natural size, is across the bedding. It was obtained from the lower, compact beds of Galena formation at J. Wright's quarry north of Lancaster, Wisconsin. White, unstained irregular patches are dolomite. The calcitic areas are highly fossiliferous. Very few fossils lie within the dolomite, and these show all stages of destruction through invasion of dolomite crystals.

3. Nor do dolomites show the relation to time that would have resulted if average underground waters had effected their formation in the course of ages. The Precambrian of North America contains vast thicknesses of nearly pure dolomite in the 49th parallel section and in the Lake Superior region, but the thick Grenville limestones of southeastern Ontario are remarkably low in magnesia. Dolomites predominate in the Cambrian and Lower Ordovician of the Appalachian province and in the Mississippi Valley, but the Cambrian of the Western States seems to have mainly limestones. Limestones are more important than dolomites in the Middle and Upper Ordovician of the United States excepting in the Upper Mississippi Valley and in the Western States. In the eastern part of the United States the Ordovician is an important source of Portland cement materials, and probably includes the most extensive deposits of high calcium limestones of the United States. The Silurian has some limestones, but dolomites dominate in the Appalachians and in the Mississippi Valley. In the Salina beds dolomites occur with salt and gypsum. Limestones are more abundant than dolomites in the Devonian. The Mississippian, too, has very little dolomite, but has great limestone beds in the Mississippi Valley. Mississippian dolomites, however, are associated with salt and gypsum in southern Michigan. The Pennsylvanian has many limestone, but almost no dolomite, beds in the Eastern States, the Mississippi Valley, and in Texas. The western undivided Carboniferous has both limestones and dolomite. In Montana early Carboniferous dolomite beds show evidences of having been laid down under arid conditions. In the Permian dolomite beds are common with gypsum and red beds, chiefly non-marine deposits, or at least without distinctly marine features. The Permian of the open seas has limestones, but little dolomite. The writer has not made a detailed study for Mesozoic and Tertiary beds, but they seem to have more limestones than dolomite. Many Tertiary coral reefs of the southern Pacific, however, are either partially or wholly dolomitized. It may be seen from this necessarily brief summary that, although the carbonates of more recent times seem to be limestones largely, the older ones have considerable thicknesses of both limestones and dolomites. Pure limestones are abundant even in the Precambrian. These facts are more easily correlated with oscillations in marine conditions than with the metasomatic action of underground waters.

4. The replacement of aragonite and calcite by dolomite has been effected experimentally at ordinary temperatures by solutions comparable to sea-water, but not by carbonate solutions similar to most underground

waters. Underground waters of deserts and of great depths, however, often resemble sea-waters in concentration.

5. Many Tertiary coral reefs of the southern Pacific are more or less dolomitized. Here the only possible metasomatic agent was sea-water.

MANNER OF MARINE DOLOMITIZATION

THE PROCESSES

It is conceivable that marine dolomites may have resulted from one or more of the following processes:

Replacement of lime carbonate;
Recrystallization of MgO-bearing aragonite and calcite skeletons;
Crystallization from water permeating the sediments of the sea-bottom;
And direct chemical precipitation.

DOLOMITIZATION BY REPLACEMENT OF LIME CARBONATE AT THE SEA-BOTTOM

Evidences of replacement.—Many facts argue for the development of marine dolomites by the replacement of lime carbonate. Some prove it. Others fit more than one interpretation equally well. Evidence for this process obtained by direct study of samples is presented under the following headings:

Relations of dolomite grains to the bedding.
Relations of dolomite to fossils.
Relations of dolomite grains to each other and to calcite grains.
Relations of dolomite to pervious marine structures.

Relations of dolomite grains to the bedding as shown by stains.—Plates 23 and 24 show a typical mixture of primary calcite and dolomite differentiated by stains. The bedding is horizontal. The bunchy, irregular distribution of the dolomite proves that it was formed chiefly by reactions within the sediments and not by direct precipitation. The latter process would have caused a more even arrangement of the dolomite particles. The existing relation of the dolomite grains respective to the bedding may be due to replacement of lime carbonate and to crystallization of dolomite from the sea-waters in the ooze. Other facts give stress to the process of replacement.

Relations of dolomite to fossils.—Well preserved fossils are less abundant in dolomites than in limestones. Silicified forms, however, are as a rule very fine. Microscopic fossils were rare in the dolomite samples studied, but the limestones were usually full of them. Weller[13] found the fossils in dolomite to be about the same in kind and development as

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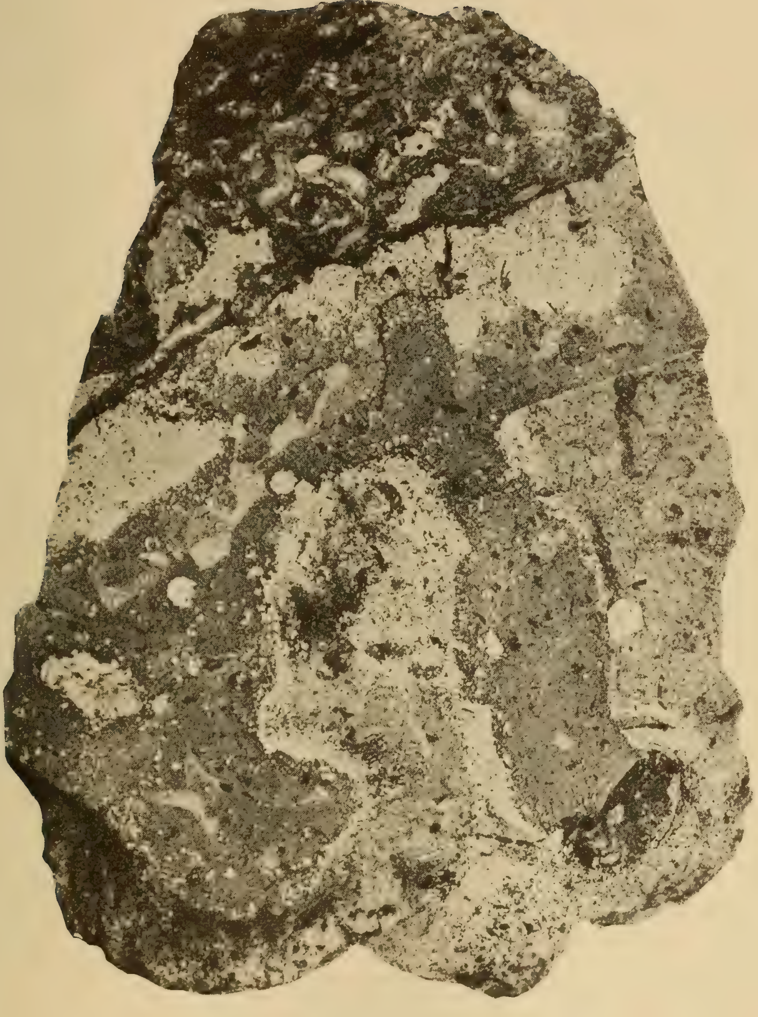
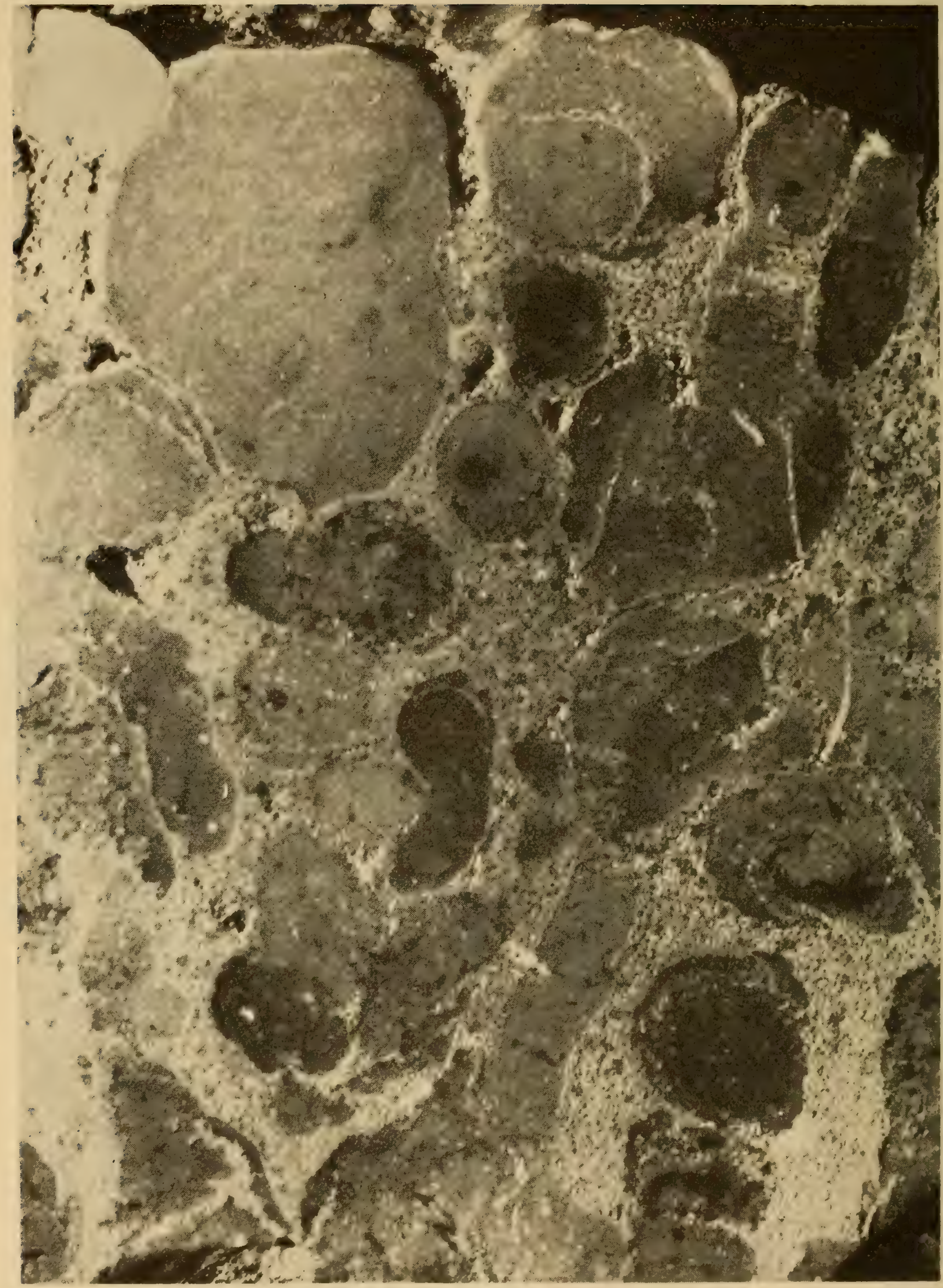
[13] Stuart Weller: Bull. Geol. Soc. Am., vol. 22, 1911.



LIMESTONE FROM LANCASTER, WISCONSIN

The white areas are dolomite, the darker ones calcite. Dolomite is irregularly scattered with reference to the bedding. The shape of the dolomitic patch in the lower central portion suggests relationship to an organic structure, possibly algal. The calcitic portion is fossiliferous. Fossils in dolomite are scarce. This specimen, which is natural size, was obtained from the basal compact beds of Galena formation at J. Wright's quarry, Lancaster, Wisconsin.



GALENA LIMESTONE FROM ETNA, WISCONSIN

The dark-stained bodies are cross-sections of algal secretions. The white, granular cement is dolomite. Algal bodies are invaded by dolomite along border and in cracks. This specimen, magnified 10 times, is from the basal beds of Galena limestone near Etna, Wisconsin.

in limestones of similar age; hence the inferior number of fossils in dolomite can not be regarded as due to sedimentary conditions unsuitable to organisms, but points to the secondary destruction of fossils in dolomite. That replacement by dolomite destroys fossils was evident from many samples.

In pure dolomite beds fossils usually consist of hollow casts surrounded by perfect molds of dolomite (see plate 22, figure 1). Evidently the shell in plate 22 was buried in a dolomite paste and then dissolved out after the ooze had set firm enough to preserve openings. Less commonly, the casts themselves are dolomite. This was seen only in shaly dolomitic facies of the Cincinnati shale and the Trenton limestone. The fossils in this case evidently were preserved because of the shaly molds.

In beds of mixed primary calcite and dolomite the calcitic areas are generally charged with fossil casts, mostly microscopic in size. In the dolomitic portions only the megascopic casts are seen, as a rule. These show all gradations of destruction by the invasion of dolomite crystals from the outside. In most cases, however, dolomite grains surround shells without piercing them, and appear in the hollows of shells as in plate 22, figure 2. It looks as if the shells themselves had stimulated the growth of dolomite. Perhaps ammonia or other substances generated by the decaying flesh caused dolomite to form. Not infrequently dolomite grains follow rather grotesque outlines, as in plate 24, as if their distribution had been controlled by some organic structure. Plate 26 shows the mottled limestone of Manitoba,[14] whose dark dolomitic patches Wallace has reservedly called algal in a very interesting paper.[15] As to the correctness of this view, the writer is incapable of judging. The presence of calcite casts (of shell-bearing organisms) in the dolomite areas needs explanation under this hypothesis. It seems that the worm borings which pierce all the dolomite patches and none of the limestone areas may have been an important factor in dolomitization. They admitted the sea-water to the rock. In addition, the life processes and decay of the worms may have favored dolomitization. Many of the dolomite crystals were found to project into the borings and hence are younger.

About 2 miles northeast of Sun Prairie, in Dane County, Wisconsin, is located a very interesting section suggesting that certain fossils are more susceptible to dolomitization than others. The base consists of about 20 feet of horizontal Galena-Trenton dolomite beds. This is capped by about 3 feet of mixed dolomite and limestone beds, and these in turn by several feet of nearly pure limestone. In the mixed beds the dolomitized masses are dome-shaped, about 2 feet high and 3 feet in diameter at the base. The bedding cuts across the domes as shown in figure 2. They are not in any way related to shaly seams or to joints, but are primary structures. Ulrich[16] stated that in the domes the chief fossils dolomitized were the pelecypods, and that the pelecypods were largely in the domes, while originally calcitic tests, such as the bryozoans, crinoids, and brachiopods, were much more abundant in the limestone phases. Since the pelecypods are nearly all aragonite originally, it would seem that mound-shaped colonies of pelecypods had been more susceptible to dolomitization than the adjacent calcitic deposits.

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[14] Specimen obtained through courtesy of R. C. Wallace.

[15] R. C. Wallace: Pseudobrecciation in Ordovician limestones in Manitoba. Jour. Geol., vol. 21, pp. 402-421.

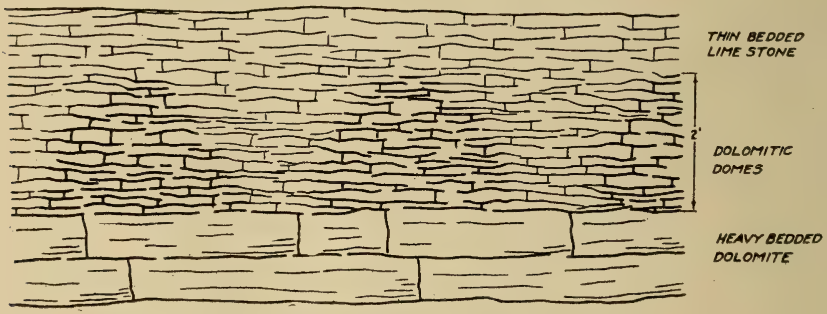

FIGURE 2.—*Diagrammatic View of Dolomite Domes*

The diagram is based on the dolomite domes in the limestone beds in the Galena-Trenton formation northeast of Sun Prairie, Wisconsin. The domes have the same bedding planes as the adjacent limestones and are not related to fissures or shaly seams. They contain numerous dolomitized pelecypods, whereas the limestone parts are rich in bryozoa, brachiopods, and crinoids.

Relations of dolomite grains to each other and to calcite grains as shown by stains.—The dolomite grains of beds lacking primary calcite varied in size from less than .01 mm. up to .15 mm. or more. A few had grains .6 mm. in width. They were, as a rule, anhedral when bounded by their own kind. The pattern in most cases is a close fitting, interlocking mosaic, apparently water-tight, judging from the lack of oxidation of the FeO in the dolomite and the occasional presence of very fresh triclinic feldspars. Some of the Lower Magnesian and Galena dolomite samples, however, are composed of loosely fitting grains fringed with limonite films. Evidenly they are quite pervious. Plate 27 shows an unusual type, a dolomitic phase of the Franconia sandstone. The dolomite rhombs are .6 mm. in diameter and include quartz grains, showing that the rhombs grew in the sediment. The matrix is a brown, opaque mass full of angular quartz grains.

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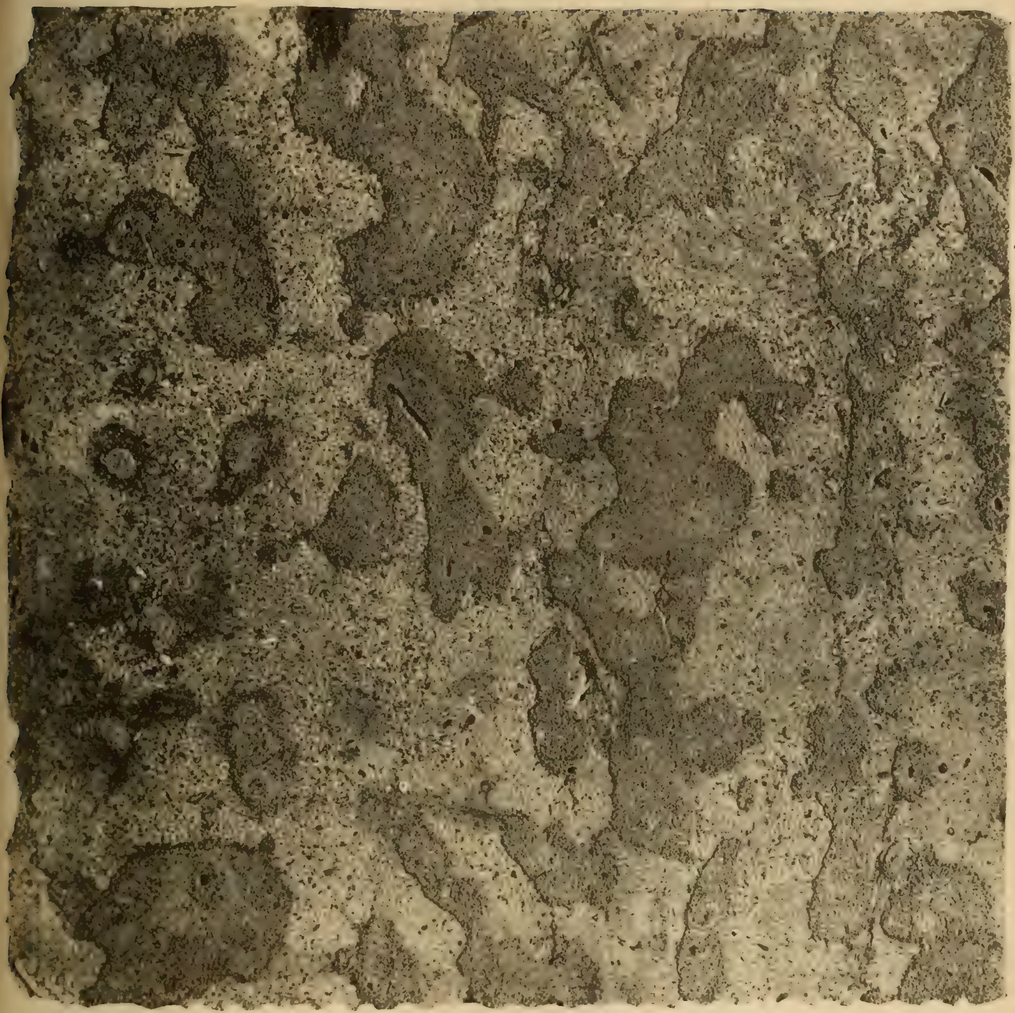
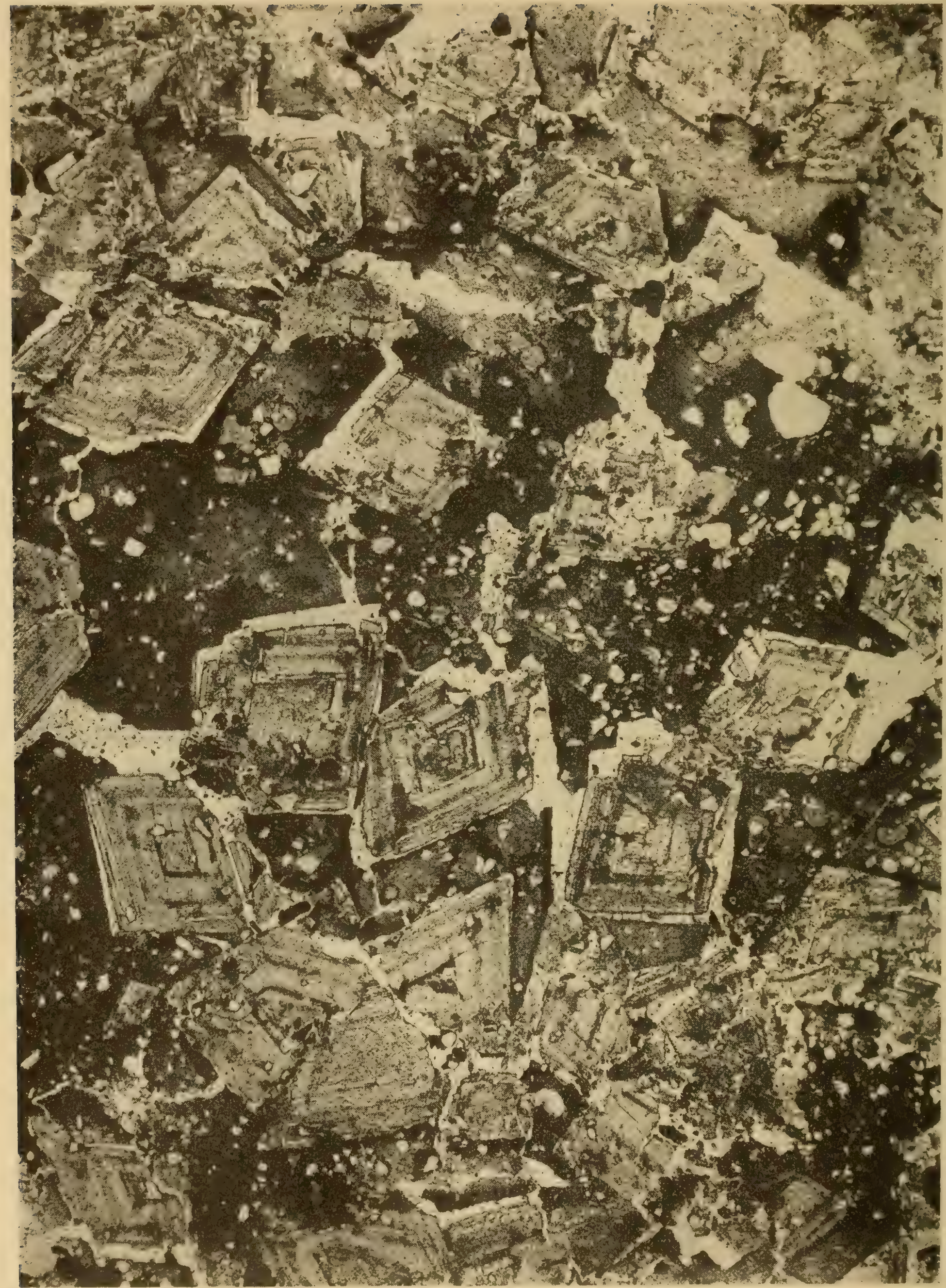
[16] Personal statement.



MOTTLED LIMESTONE FROM WINNIPEG

The dark-stained areas are nearly pure dolomite, with a few partially dolomitized casts. They are traversed by worm borings, the crater-like pits. The calcitic portion is very fossiliferous



THIN-SECTION OF DOLOMITIC PHASE OF FRANCONIA SANDSTONE

The dolomite rhombs average .6 mm. in diameter. They include quartz grains, the angular white spots, showing that the dolomite grains grew in the sediments. The matrix is opaque, limonitic, structureless, and includes numerous angular, dustlike particles of quartz. The white areas around the dolomite rhombs are holes in the slide.

Stains show that in beds containing both primary calcite and dolomite the dolomite grains are always considerably larger than the grains of calcite. They average about .4 or .5 mm. and are several hundred times the size of the calcite grains. The calcite casts are single units, as a rule. Dolomite grains bounded by grains of their own kind are anhedral, but wherever they touch calcite, even where they pierce the casts of shells, they have a strong rhombohedral habit. All the calcite grains are anhedral. The boundary between calcite and dolomite is always sharp, and the grains of calcite near the dolomite rhombs are no different in appearance than those farther away. The dolomite grains were never seen to include anhedral grains of primary calcite, and in fact only one inclusion of calcite in dolomite was observed. In this unique case a rhomb of calcite was inclosed by a dolomite rhomb.

The relations of dolomite grains to primary calcite can not all be explained by assuming that the dolomite crystallized out in the ooze where it had room to develop its individuality, for it shows the same crystal form where it invades compact calcitic casts. The fact that it is anhedral and interlocking where it is in contact with its own kind shows that the rock had considerable rigidity when crystallization occurred. Otherwise the crystals could not have crowded each other out of shape.

That replacement of calcite by dolomite has occurred is evident from the relations of the dolomite both to the matrix and to calcite fossils. There is no evidence to show that the dolomite grains got either MgO or FeO from calcite. The calcite contains no FeO. The growth of the dolomite grains can not be compared to certain secondary garnets in schists. Such garnets seem to have derived their nutriment from the schists by process of assimilation. Often undigested particles of schist materials appear within the garnet. The dolomite grains show no unassimilated calcite residuals. It looks as if the dolomite grains had started to form from a center by substituting for the calcite an exactly equal volume of dolomite. The boundaries of calcite and dolomite show that the volume of the dolomite is neither greater nor less than that of the calcite which it replaced. A part of the original calcite, about 71.2 per cent, may have been retained in the dolomite, but 28.8 per cent, calculated on the basis of constant volume, must have gone back into solution. If all the calcite had remained, a volume increase of 181 per cent would have taken place when enough MgO and FeO was added to it to make dolomite. The idea, sometimes stated, that dolomitization takes place by the substitution of one molecule of $CaCO_3$ by one of $MgCO_3$ has not been checked so far by observations. Such a change would involve a decrease in volume of 12 per cent. In the ooze the record of the change would have become lost, but not in the solid casts.

Relations of dolomite to pervious marine structures.—Attention is again called to the more frequent dolomitization of the matrix than of the casts, plate 22, figures 1 and 2, or plate 25; the frequent development of dolomite crystals in the hollows of tests, plate 22, figure 2, and the dolomitization of limestones adjacent to worm borings, plates 26 and 27. These facts seem to show that the structures which are most permeable under marine conditions are most susceptible to dolomitization. True, these structures are also permeable under emergent conditions in the sea of underground water. If underground waters, however, had been the dolomitizing agent, it would seem that the walls of fissures would be affected even more than worm borings. In the Platteville limestone at Escanaba and the mottled limestones of Winnipeg, however, it is the pervious marine structures in whose proximity dolomitization has taken place and not the joints.

DOLOMITIZATION BY RECRYSTALLIZATION OF MgO-BEARING ARAGONITE AND CALCITE SKELETONS

No facts were gathered from the Paleozoic of Wisconsin which would prove that dolomite was formed by recrystallization of MgO-bearing skeletons. The suspicion that dolomite may develop in this way is founded on the fact that the skeletons of many modern marine organisms, both calcitic and aragonitic, contain up to 14 per cent $MgCO_3$ without showing dolomite. Normal dolomite could either develop from them by the solution of the excess $CaCO_3$ or by addition of $MgCO_3$. The latter would involve an improbable volume increase. No case seems to be known where it is proven that dolomite resulted from the recrystallization of such materials. Blackwelder[17] has shown that the very pure, compact Bighorn dolomite of Wyoming has the structure of algal secretions. The fact that some modern algæ contain considerable $MgCO_3$ at least suggests that the Bighorn dolomite may have resulted from the recrystallization of MgO-bearing algal secretions. Unless they were unlike modern algal secretions and had the MgO content of a normal dolomite, the excess $CaCO_3$ must have been leached out. Since algal secretions are, as a rule, strong and compact, the removal of $CaCO_3$ from them would have given rise to considerable pore space. Of this the rock shows no evidence.

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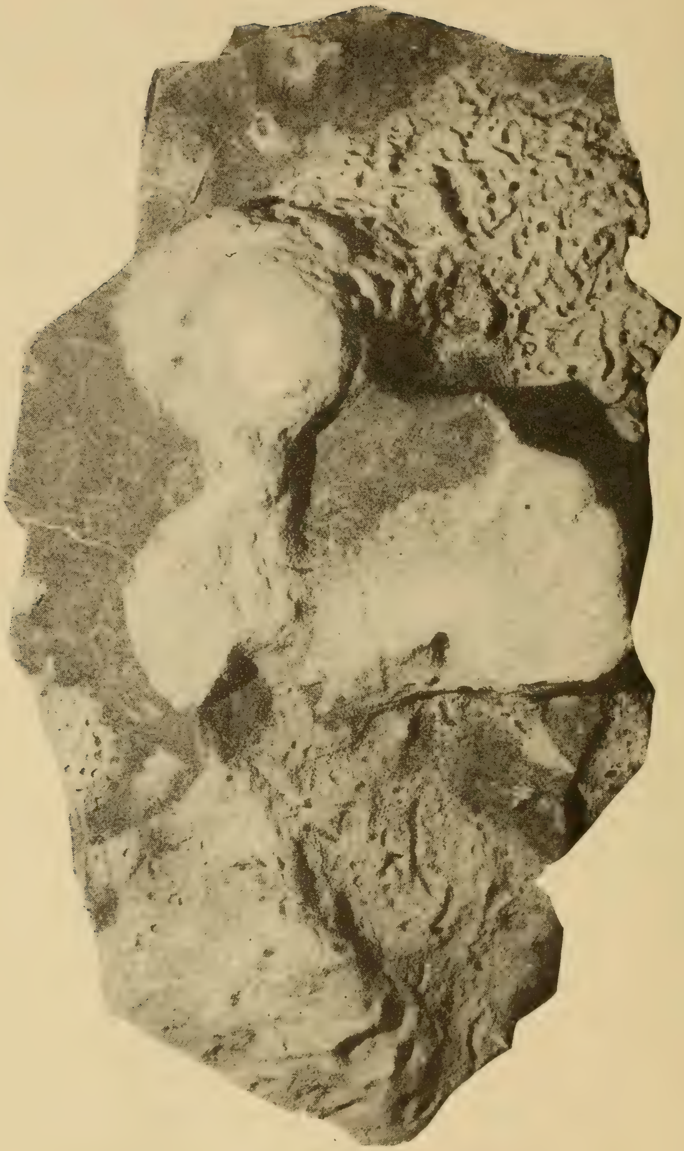
[17] Eliot Blackwelder: Origin of Bighorn dolomite, Bull. Geol. Soc. Am., vol. 24, pp. 607-624.



DOLOMITE FROM THE TRENTON OF ESCANABA, MICHIGAN

The worm-bored areas are dolomite, the compact portions primarily calcite. Natural size

CRYSTALLIZATION OF DOLOMITE FROM SEA-WATERS PERMEATING THE SEDIMENTS OF THE SEA-BOTTOM

The bunchy, irregular distribution of dolomite grains in mixed beds of limestone and dolomite, as shown by stains, may be due in part to the direct crystallization of dolomite grains from waters in the ooze of the sea-bottom. The inclosure of dolomite grains in very fine-grained, compact calcite masses (also shown by plate 22) suggests the same thing. Proof of this process was not obtained from the samples studied. Skeats found dolomite in druses and vugs of recently uplifted coral reefs of the southern Pacific coral reefs, indicating that direct crystallization of dolomite from sea-waters does take place under certain conditions. Certain dolomite rhombohedra in the oozes of the Mediterranean[18] may be due to the same process.

DIRECT PRECIPITATION OF DOLOMITE FROM THE SEA

The grain of some dolomites is so fine (less than .01 mm.) as to suggest that they are chemical precipitates. The relatively large size of the dolomite grains in mixed beds of dolomite and calcite where the dolomite is clearly a replacement adds weight to the view that the fine-grained dolomite beds are of a different origin. In respect to grain, the fine-grained dolomites resemble the bacterially precipitated lime carbonate oozes of modern seas. Because of the FeO content of dolomites, it is improbable that any of them were thrown out of the upper strata of sea-water, but only in the lower layers near the bottom where reducing conditions would be probable.

Conditions of Dolomitization in the Sea

CRITICAL STATE BETWEEN LIMESTONE AND DOLOMITE DEPOSITION

The dominance of pure limestone and dolomite over mixed beds of the two, as shown by stains and analyses, and the alternations of fairly pure limestone and dolomite beds indicate that the critical state between limestone and dolomite depositing conditions is a narrow one, and that when the borderland between the two is reached moderate changes, as a rule, halt deposition of one kind and substitute another. Special conditions may at times have tempered down the full effectiveness of dolomite-producing conditions. In many mixed beds it is evident that the calcite represents compact residuals which escaped dolomitization because of their impermeable condition. For example, a certain bed in the Galena-

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[18] O. B. Boggild: Report of the Danish Geographical Expedition, 1908-1910.

Trenton formation at Etna, Wisconsin, shows a mat of cylindrical calcite individuals averaging about .5 inch in length and .2 inch in diameter—pronounced algal secretions by Dr. E. O. Ulrich,[19] which are partially dolomitized on the surface and along cracks. Plate 25 shows a cross-section of one of these masses. The matrix in which they are embedded is a granular dolomite. Where the algal growths are absent the bed consists wholly of the dolomite. It is not at all true, however, that limestones in general have escaped dolomitization because of compactness (see tables 1 and 2, page 438).

Diagram 1 shows that, as a rule, the beds of mixed calcite and dolomite have more insoluble constituents than the pure limestones and dolomites. The significance of this is doubtful. Since muds are more common in the carbonates than sands, it seems likely that dolomitization was checked by the sealing effect of the muds.

DEPTH OF WATER

All the Paleozoic dolomites of Wisconsin were laid down in shallow water. This is evidenced by reef structures, ripple-marks, conglomerates, cross-bedding, sun cracks, and association with sands and muds. Most dolomites appear to have been deposited in shallow seas. It does not follow, however, that deep waters prohibit the development of dolomite. It is equally true that most marine limestones exposed on the lands are of shallow-water origin.

TEMPERATURE OF WATER

The type of life preserved in the dolomites studied proves that they were formed in warm seas. In fact, no proof could be found anywhere of dolomites having formed under distinctly frigid conditions. Experiments indicate that under certain conditions dolomitization is stimulated by temperatures above 30° C. Deposition in warm seas is not peculiar to dolomites, but is equally characteristic of most limestones.

COMPOSITION OF SEA-WATER

Special emphasis is given to the FeO content of dolomites which was brought out by staining methods and to its absence in the primary calcite grains of about 300 samples mostly from Wisconsin, but including some from Wyoming and Winnipeg. Vein calcite examined usually showed FeO by staining. Shaly streaks in limestones and dolomites unless strongly oxidized also reacted for FeO. The difference in FeO content of primary calcite and dolomite was so striking as to raise the question how general it is. Limestone analyses are not as delicate a measure of the FeO content of calcite as stains, since some of the FeO may be in shaly portions, but they confirm the results of staining very well. Seventeen analyses of limestones reported in Bulletin 591, United States Geological Survey, averaged .18 per cent acid soluble FeO; 5 analyses of dolomite from the same publication averaged 1.10 per cent acid soluble FeO. Only those analyses showing soluble FeO were taken.

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[19] Personal communication.

It is certain from this that the dolomites studied were formed under reducing conditions, for ferrous oxide in aqueous solutions is very easily oxidized. Since they all bear the marks of shallow-sea deposits, it is almost certain that they were not precipitated directly from the upper strata of sea-water. Wave action must have aerated the waters excepting perhaps right near the bottom, where the air may have been excluded by the gases of decay. One would infer that dolomite was formed at the sea-bottom, where decaying flesh and plant material gave rise to reducing conditions.

No definite comparison can be made between the salinity of dolomite and limestone-depositing seas. Experiments show that high concentration of the magnesium sulphates and chlorides favors the change from calcite to dolomite. The association of dolomites rather than limestones with inclosed basin deposits, gypsum and salt beds also suggests that salinity may be an important factor in dolomitization. It does not appear to be true, however, that the open seas in which dolomite formed were very much more saline than those from which limestones were deposited. The difference in salinity was not sufficient to cause a difference in the kind and development of fossils in the two, according to Weller. If a granular marine-deposited limestone bed free from impervious marine structures could be found to grade into granular marine-formed dolomite deposited at exactly the same time, one would be forced to the view that the composition of the sea-water was not always a critical factor in dolomitization. One would look to either temperature, pressure, or organic processes as more decisive. Such a bed does not appear to be known, and the opinion that salinity is an important factor in dolomitization therefore seems to be supported both by field and experimental facts.

SUMMARY

MARINE OR POST-MARINE ORIGIN OF DOLOMITE

Most dolomites were deposited in the sea. A minority of dolomites were formed by the replacement of limestones by underground waters.

The latter are recognized by their relation to fissures, faults, and other secondary openings.

Direct observations by the writer and published facts showing that the majority of dolomites are marine in origin were cited. The direct observations reported were as follows:

1. Pure dolomites and limestones, as shown by staining and analyses, are far more abundant than mixed beds of limestone and dolomite.

2. The occurrence of calcitic casts in dolomite or of hollow casts bounded by perfect molds indicates that the casts were deposited in dolomite.

3. Some dolomite rhombs are imbedded in a hornlike impervious mass of fine-grained marine calcite. They evidently were formed in the ooze contemporaneously with the calcite.

The published facts which were set forth in support of the conclusion that most dolomites were developed in the sea are:

1. The distribution of most dolomites is related to stratigraphic planes and not to fissures, faults, etcetera. Mixtures of dolomite and limestone within a single bed, as a rule, are also sedimentary in origin, since they are not related to secondary openings.

2. Limestone and dolomite formations frequently alternate.

3. Dolomitization generally shows no relation to the present pore space of beds.

4. The abundance of both limestones and dolomites in the strata of all ages does not fit the view that dolomites are wholly the metasomatic products of underground waters. Their time relations seem to have resulted from oscillations in marine conditions of deposition.

5. Artificial replacements of calcite and aragonite by dolomite have been effected by solutions comparable to sea-waters, but not by carbonated waters similar to the average underground waters.

6. Many coral islands of the Pacific are dolomitized. Sea-waters alone could have been responsible for this change.

MANNER OF MARINE DOLOMITIZATION

Marine dolomitization may have been accomplished by direct precipitation and by reactions within the sediments of the sea-bottom, such as replacement of lime carbonate, recrystallization of MgO-bearing lime carbonate skeletons, and crystallization of dolomite from sea-waters in the ooze.

The results of staining show that the replacement of lime carbonate is an important process. Replacement is proven by the bunchy, irregular distribution of dolomite grains with respect to the bedding in mixed beds of limestone and dolomite; the partial to complete replacement of lime carbonate skeletons by dolomite, and by cases of local dolomitization adjacent to or within pervious marine structure, such as worm borings, shell cavities, etcetera.

Dolomite grains in contact with their own kind are generally anhedral and at best only roughly rhombohedral. Those in contact with calcite grains were under all conditions found to be rhombohedral, whereas all calcite grains were anhedral and smaller than the dolomite rhombs with which they occur. In no case examined by the writer did dolomite grains contain undigested calcite residuals. The sharp borders between calcite and dolomite grains and the knife-edge contacts of dolomite invaders in casts prove that certain replacements of calcite by dolomite were accomplished without volume change. No evidence could be found to show that it ever takes place with volume change.

Convincing evidence could not be found for dolomitization by recrystallization of MgO-bearing lime carbonate skeletons. It is suspected that it takes place from the fact that many modern lime carbonate skeletons contain up to 14 per cent $MgCO_3$ without showing dolomite.

Crystallization from the waters in the ooze is suggested by the inclusion of dolomite rhombohedra in dense, fine-grained masses of calcite, but replacement of lime carbonate before consolidation explains this relationship equally well. In recently uplifted coral reefs the presence of dolomite crystals in druses and vugs shows that crystallization from seawaters within the sediments does occur under certain conditions.

Proof of direct precipitation of dolomite from the sea was not found. The fine grain of some dolomites, a grain much finer than that of the dolomites which are clearly due to replacement, and the similarity in grain of the fine-grained dolomites to modern bacterially precipitated lime carbonate oozes suggest strongly that these fine-grained dolomites are chemical precipitates. If they are precipitates they probably were thrown out of the lower strata of water, since they contain FeO. Only the lower strata of water could be expected to be reducing in action and thus permit the precipitation of FeO.

CONDITION OF MARINE DOLOMITIZATION

Marine dolomites were mostly deposited in warm, shallow seas; but this seems to be equally true of most limestones. A minority were laid down in very saline waters. The salinity of the open seas in which most of them were formed was not sufficiently different from that of limestone-depositing seas to impress itself on the fossils. Experiments show that increase in salinity stimulates dolomitization.

The dominance of pure limestones and dolomites brought out by stains shows that the margin between dolomite and limestone-bearing conditions is a narrow one, and hence near the critical stage slight changes in chemical conditions may completely change the nature of deposition.

Stains showed that all of the several hundred dolomite samples studied contained FeO. It was absent in all primary calcite grains tested. The uniform presence of FeO in marine dolomites shows that this compound is a primary constituent. Marine dolomites therefore were formed under reducing conditions. In the shallow seas in which they formed reducing conditions could be looked for only within the ooze where decay was rampant or in the lower strata of sea-water, below the aerating effect of wave action.

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A CLASSIFICATION OF METAMORPHIC ROCKS*

BY WILLIAM J. MILLER

(Presented before the Society December 28, 1916)

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INTRODUCTION

The purpose of this paper is to present a comprehensive classification of metamorphic rocks, the attempt being made to work out a satisfactory scheme without the introduction of new terms. In this proposed classification the main principles are based on (1) origin of the rocks, (2) rock structure, and (3) composition. Since it is necessary to have certain important terms pertaining to metamorphic rocks clearly defined and differentiated, this matter is considered at some length. After the terms are defined, they are, it is believed, consistently employed in the classification presented. In geological literature there is much confusion regarding the nomenclature of metamorphic rocks, and, in many cases, after a writer has clearly defined a term this same term is used in a different sense in the same book or paper.

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* Manuscript received by the Secretary of the Society January 6, 1917.

Apparently there are few published attempts to make comprehensive classifications of metamorphic rocks. Many text-books, as, for example, Pirsson's "Rocks and Rock Minerals," give simple groupings for convenience of discussion. In Van Hise's great work, "A Treatise on Metamorphism," there is no comprehensive classification of metamorphic rocks. In fact, Van Hise[1] there says: "At the present time there is not only no consensus of opinion concerning a classification of such rocks, but there is not even an approximation to a consensus of opinion as to the principles on which a classification should be based." Leith and Mead, in their recent book on "Metamorphic Geology," give no classification of metamorphic rocks.

Kemp,[2] in his "Handbook of Rocks," gives a fairly comprehensive classification, which, in many respects, is an excellent one. The major divisions are products of (1) contact metamorphism, (2) regional metamorphism, and (3) weathering. The contact rocks are subdivided into (*a*) internal and (*b*) external products, while the regional rocks are subdivided into (*a*) gneisses derived from igneous rocks, as, for example, granite gneiss, syenite gneiss, etcetera; (*b*) gneisses derived from sedimentary rocks, as, for example, granitic gneiss, syenitic gneiss, etcetera; (*c*) crystalline schists; (*d*) quartzites and slates; (*e*) crystalline limestones, and (*f*) ophicalcites, serpentines, and soapstones. Some criticisms of this scheme are as follows: The impossibility of always separating the crystalline schists from the gneisses on the basis of differences in mineralogical composition, it being required by Kemp that the gneisses must have the mineralogy of the granitoid igneous rocks; the inadvisability of using such terms as "granitic gneiss," "syenitic gneiss," etcetera, for derivatives from sedimentary rocks, this certainly not being in harmony with the excellent suggestions made by Gordon[3] many years ago; and the failure to provide places for such important types as the so-called primary gneisses, the injection gneisses, and gneisses and schists of unknown origin.

Perhaps the most elaborate classification of foliated rocks yet proposed is that by Grubenmann.[4] He makes twelve groups of schists and gneisses as follows: (1) orthoclase gneisses, (2) alumina-silicate gneisses, (3) plagioclase gneisses, (4) eclogite and amphibolite, (5) magnesian-silicate gneisses, (6) jadeite rocks, (7) chloro-melanite rocks, (8) quartzitic rocks, (9) lime-silicate rocks, (10) marbles, (11) iron oxide rocks, and (12) alumina-oxide rocks. Further, the rocks in each group are regarded as having been produced in three zones within the earth's crust, namely, an upper, a middle, and a lower. It is argued that each of these zones is dominated by certain definite physical conditions, resulting in the production of rock types characteristic of each zone. It is the present writer's belief that this classification is altogether too elaborate and artificial to be practicable in the light of our present knowledge of these rocks. In the first place, twelve really well defined groups of schists and gneisses, based on chemical composition, can not be made, because there are endless gradations back and forth from one group into another. In the second place, the attempt to classify all schists and gneisses into three zones according to depth reminds us of the idea, long maintained by Rosenbusch, that igneous rocks show characteristics whereby they can be classified as of surface, dike, or plutonic origin. In an excellent review of Grubenmann's scheme, Leith and Mead[5] say: "It puts an emphasis on depth as a controlling factor in anamorphism which does not seem to the writers to correspond to actual field observations. . . . Depth is only one of the factors determining these differences in intensity. . . . Field conditions indicate that the same conditions which will produce certain schists of the 'upper' group from one type of rock may produce schists of the 'middle' or 'lower' groups from another type of rock."

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[1] C. R. Van Hise: U. S. Geol. Survey Mon. 47, 1904, p. 775.

[2] J. F. Kemp: Handbook of Rocks, 1911, p. 160.

[3] C. H. Gordon: Bull. Geol. Soc. Am., vol. 7, p. 122.

[4] U. Grubenmann: Die kristallinen Schiefer, vol. 2, 1907, pp. 172-173.

Discussion of important Terms

METAMORPHISM

According to Van Hise,[6] "metamorphism means any change in the constitution of any kind of rock." This is a use of the term in the very broadest sense, and would include even such changes as the transformation of clay into shale, mere mechanical breaking up or disintegration of rocks, etcetera. Usually, however, rocks produced by the processes just mentioned are not considered to be metamorphic rocks.

The following definition of metamorphism, based essentially on that by Pirsson,[7] gives the meaning of the term as it is employed in this paper. *Metamorphism means any change in mineral composition, structure, or texture of an igneous or a sedimentary rock whereby the original rock character has been notably changed.* Though it is impossible always to sharply distinguish between the original rocks and their metamorphic derivatives, because there are all sorts of gradations, "there comes a point in the change of each original rock . . . where its characters and relations to other rocks have become so individual that, for practical purposes, it is best regarded as a distinct kind of rock."[8]

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[5] Leith and Mead: Metamorphic geology, 1915, pp. 188-193.

[6] C. R. Van Hise: U. S. Geol. Survey Mon. 47, 1904, p. 32.

FOLIATION AND FOLIATES

By most writers the term "foliation" (or "foliated rock") is applied in a very broad sense to metamorphic rocks only, and there is pretty general agreement as to the meaning of the term. A few definitions from well known sources will suffice to bring out the ideas most commonly held.

J. Geikie[9] says: "In a foliated rock (or schist) the constituent minerals . . . are arranged in more or less parallel layers."

Kemp[10] defines foliation as "the banding or lamination of metamorphic rocks as distinguished from the stratification of sediments."

Scott says "foliation is the arrangement of the constituent mineral particles of a rock into rudely parallel planes or undulating surfaces."

Pirsson[11] uses the term "schistose texture" in a very broad sense as one of the eminent characteristics of metamorphic rocks, and the term "foliated" as one of three varieties of that texture. This is an unusually restricted use of the term.

In the attempt to make a clear distinction between foliated rocks in general and true gneisses in particular (see below), the writer suggests the following definition: *A foliate is a metamorphic rock which, due to pressure or flowage under pressure, exhibits a more or less clearly defined parallelism of certain or all of its mineral constituents, giving the rock a streaked, lenticular, banded, or laminated structure.* Such a rock possesses "foliation," and, as suggested by Bastin,[12] "foliate" is a convenient comprehensive term which may be applied to any rock showing a foliated structure. The above definition, while essentially in agreement with most definitions of "foliation," is thought to be rather more precise. As thus defined, the foliates include the so-called "primary gneisses," the ordinary gneisses and schists, and slate and phyllite.

MEANING OF "GNEISS"

According to Van Hise,[13] a gneiss is "a banded (metamorphic) rock, the bands of which are petrographically unlike one another and consist of

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[7] L. V. Pirsson: Rocks and rock minerals, 1909, p. 333.
[8] L. V. Pirsson: Rocks and rock minerals, 1909, p. 333.
[9] J. Geikie: Structural and field geology, 1908, p. 74.
[10] J. F. Kemp: Handbook of Rocks, 1911, p. 209.
[11] L. V. Pirsson: Rocks and rock minerals, 1909, p. 341.
[12] E. S. Bastin: Jour. Geol., vol. 17, 1909, p. 449.
[13] C. R. Van Hise: U. S. Geol. Survey Mon. 47, 1904, p. 782.

interlocking mineral particles." This definition clearly includes the so-called "primary gneisses," which, in the writer's opinion, should not be called true gneisses (see below). Also, many rocks—for example, granite-gneiss, commonly called gneisses—not only are not truly banded, but also they are not distinctly cleavable in harmony with Van Hise's definition of schist as given below. Where, then, would such rocks be classified?

Harker[14] says that "a gneiss is a crystalline rock possessing a banded or streaky character, due to the association or alternation of different lithologic types in one rock-mass or to the occurrence of bands or lenticles specially rich in some particular constituent of the rock." This definition, except for the fact that it also clearly includes so-called "primary gneisses," is a good one, though somewhat long and involved because of so much attention to the meaning of the foliated structure.

According to Leith and Mead,[15] "gneissic structure means a banding of constituents, of which feldspar is important, with or without the parallel dimensional arrangement necessary for rock cleavage." Here, again, the so-called "primary gneisses" would be included. Also, as in many other definitions of "gneiss," the presence of feldspar is expressly required; but this is open to serious criticism, because, according to this conception, certain secondarily foliated rocks commonly known as pyroxenite-gneiss, peridotite-gneiss, marble gneiss, etcetera, are really not gneisses at all. If these are not gneisses, what should they be called? But why eliminate such rocks from the category of true gneisses?

According to Pirsson,[16] "the only general definition of gneiss which will cover all cases is that they are metamorphic rocks, composed of feldspar, with other minerals, which have a certain characteristic (foliated) texture." Apparently, however, this definition does not cover all cases, since such feldspar-free rocks as pyroxenite-gneiss, pyroxene-garnet gneiss, etcetera, are strictly excluded.

Merrill[17] says: "Gneisses are holocrystalline granular rocks, as are granites, but they differ in that the various constituents are arranged in approximately parallel bands or layers" and "the composition of the gneisses is essentially the same as that of the granites." This definition is open to the same criticisms as regards the feldspar content and the inclusion of the so-called "primary gneisses." Merrill gives, and speaks highly of, Gordon's classification of gneisses (referred to beyond in this paper); but, if a gneiss must contain feldspar, this certainly does not harmonize with Gordon's scheme.

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[14] A. Harker: Petrology for Students, 1897, p. 320.

[15] Leith and Mead: Metamorphic geology, 1915, p. 179.

[16] L. V. Pirsson: Rocks and rock minerals, 1908, p. 351.

[17] G. P. Merrill: Rocks, rock weathering, and soils, 1906, pp. 142-143.

Kemp[18] defines a gneiss as "a laminated or foliated granitoid rock that corresponds in mineralogical composition to some one of the plutonic rocks." So-called "primary gneisses" are, of course, here included. Furthermore, certain rocks which, by all means, should be called gneisses do not possess a true granitoid texture, while still others—for example, pyroxene-garnet gneiss, quartz-biotite-graphite gneiss, marble gneiss, etcetera, do not have plutonic rock mineralogical compositions.

Finlay's[19] definition is much like that by Kemp, namely: "Gneiss is a metamorphic rock with distinct lamination and the mineralogy of a rock in the igneous granitoid series." To say that a gneiss must be distinctly laminated is either using the term "laminated" incorrectly or certain foliated crystalline rocks must be excluded from the category of gneisses.

Gordon[20] says the term "gneiss" should be used in its broader structural sense for all (metamorphic) rocks showing a laminated or banded structure, and in which this structure is not known to be due to differential movements of an igneous mass before its final consolidation. This is the only definition thus far cited which clearly excludes the so-called "primary gneisses" from the true gneisses; also it does not require the presence of feldspar in a gneiss. But, according to this definition, non-crystalline or only partially crystalline foliated rocks like the slates and phyllites would be called gneisses, while foliated crystalline rocks neither truly laminated nor banded, but with a lenticular structure, would not be included.

Bearing in mind the above conceptions and criticisms regarding the meaning of the term "gneiss," the writer proposes the following definition: *A gneiss is a foliated megascopically crystalline rock of secondary origin produced essentially by pressure.* Such a rock possesses a gneissose or gneissic structure. Above all, a gneiss must possess a foliated structure, and, since the term "foliate" is broader in its scope than gneiss and has already been defined, it is only necessary to mention the foliated structure as a part of the definition of a gneiss. Next, a gneiss must be notably crystalline in order to exclude such rocks as slates and phyllites. Again, a gneiss must be decidedly secondary in origin and produced essentially by pressure in order to exclude from the true gneisses the so-called "primary gneisses," this matter being discussed below. This definition does not regard mineralogical content, and is thus in harmony with Van Hise, Gordon, and others who strongly urge the use of the term "gneiss" in a purely structural sense. It is impossible to consistently use the term "gneiss" in a dual sense—that is, structural and mineralogical. Finally, the definition here proposed does not limit gneisses to distinctly banded or laminated metamorphic rocks, but includes those with lenticular structure as well.

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[18] J. F. Kemp: Handbook of Rocks, 1911, p. 212.

[19] G. I. Finlay: Igneous rocks, 1913, p. 14.

[20] C. H. Gordon: Bull. Geol. Soc. Am., vol. 7, p. 122.

MEANING OF "SCHIST"

There is a strong tendency among American geologists to make the essential difference between gneisses and schists structural rather than mineralogical. Practically all American students of the subject consider both gneisses and schists to be crystalline foliated rocks, and most consider schists to be more perfectly or finely foliated, causing such rocks to cleave more or less readily in one direction. As clearly stated by Kemp:[21] "Gneisses differ from schists in the coarseness of the laminations (foliation), but as these become finer they pass into schists by insensible gradations."

European geologists frequently use the term "schist" with a much broader meaning, practically synonymous with "foliated rock." Thus A. Geikie[22] says: "Gneisses denote the coarser schists"; J. Geikie[23] speaks of "a foliated rock or schist"; and Grubenmann[24] uses the term "Schiefer" to include all foliated rocks.

The following definitions (one from an English writer) give a fair idea of the meaning of "schist" to most American geologists. According to Van Hise:[25] "Schist is defined to include those cleavable (metamorphic) rocks the cleavage pieces of which are like one another and the mineral particles of which are for most part so large as to be visible to the naked eye." This definition differs from most others in requiring that the cleavage pieces be like one another.

Harker[26] says: "Schists are crystalline rocks which possess a parallel arrangement of some or all of their elements . . . and which have in consequence the property of splitting with more or less facility in a definite direction (schistosity)." In short, Harker considers gneisses and schists to be practically the same except that the latter are more or less readily cleavable.

Leith and Mead[27] say: "A schist always has a parallel dimensional arrangement (of constituents necessary for rock cleavage) and may or may not contain feldspar."

Pirsson[28] uses the term "schistose" in a broad sense, practically synonymous with the foliated structure of a metamorphic rock, which thus suggests the European meaning of the term.

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[21] J. F. Kemp: Handbook of Rocks, 1911, p. 133.
[22] A. Geikie: Text-book of Geology, 1903, p. 134.
[23] J. Geikie: Structural and field geology, 1908, p. 74.
[24] U. Grubenmann: Die kristallinen Schiefer, vol. 2, 1907, p. 21.
[25] C. R. Van Hise: U. S. Geol. Survey Mon. 47, 1904, p. 779.
[26] A. Harker: Petrology for Students, 1897, p. 318.
[27] Leith and Mead: Metamorphic geology, 1915, pp. 179-180.
[28] L. V. Pirsson: Rocks and rock minerals, 1908, p. 340.

Merrill[29] says schists "are a large and extremely variable series of rocks, differing from the gneisses mainly in the lack of feldspar as an essential constituent." A foliated granite is, accordingly, a gneiss, while a foliated peridotite is a schist. Thus no structural difference between the gneisses and schists is made, and this is very unusual among American geologists.

According to Kemp,[30] schists are "thinly laminated, metamorphic rocks which split more or less readily along certain planes approximately parallel." Strictly in harmony with this statement, slates would be included with schists. They would be excluded by limiting the schists to megascopically crystalline metamorphic rocks.

Finlay[31] says: "Schist is a foliated metamorphic rock which will split into thin slabs or flakes much more readily than gneiss does." Here, again, slates would be included.

Keeping in mind the above statements regarding the meaning of the term "schist," the writer proposes the following definition: *A schist differs from a gneiss in being more finely foliated and capable of being split (cleaved) into thin layers.* Such a rock possesses a schistose structure. As thus defined, schists are simply more or less perfectly cleavable gneisses, and the gneissose structure passes into the schistose structure by insensible gradations.

META-IGNEOUS ROCKS[32]

FOLIATES

Primary ortho[33]-foliates.—These foliated igneous rocks have been produced essentially by magmatic flowage or differential movements in igneous masses before complete consolidation. Because their foliation has been developed before final consolidation of magmas, they are called "primary" foliates. These rocks comprise the so-called "primary gneisses," but the writer strongly urges that these be removed from the category of true gneisses, (1) because their foliation is not strictly of secondary origin, as is true of all other rocks called gneisses, and (2) because they are really intermediate between truly unaltered and altered igneous rocks. In fact, there is some ground for excluding these from the class of metamorphic rocks altogether; but, because (1) they possess genuine foliation which is so characteristic of most of the common metamorphic rocks, (2) the foliation is impressed on them after nearly complete consolidation of the magmas, and (3) they almost always exhibit more or less granulation, it seems clearly advisable to classify the primary ortho-foliates with the metamorphic rocks. Certainly, however, they should not be called true gneisses, which always ought to be regarded as of strictly secondary origin. Following the suggestion of Gordon,[34] the structural term "gneissoid," meaning literally "resembling a gneiss," is applied to these rocks. Thus we have gneissoid granite, gneissoid diorite, etcetera. In rare cases, where the gneissoid structure is so perfectly developed that the rock cleaves more or less readily, the term "schistoid" may be employed. Fine large-scale examples of gneissoid granites have recently been described by Adams and Barlow[35] in Ontario and by the present writer[36] in the Adirondacks.

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[29] G. P. Merrill: Rocks, rock weathering, and soils, 1906, p. 146.

[30] J. F. Kemp: Handbook of Rocks, 1911, p. 252.

[31] G. I. Finlay: Igneous rocks, 1913, p. 14.

[32] Instead of the long terms "meta-igneous rocks" and "meta-sedimentary rocks," it is suggested that "meta-igs" and "meta-seds," respectively, be used, these being short, convenient, self-explanatory designations. Clearly, however, the possible use of these terms would in no wise affect the principles of the classification set forth in this paper.

[33] The prefixes "ortho-" and "para-" are used in this paper in the generally accepted sense to indicate metamorphosed igneous and sedimentary rocks, respectively.

Secondary ortho-gneisses and schists.—These are so named because they are crystalline, foliated, igneous rocks of strictly secondary origin. Foliates of this kind are produced essentially by pressure, often accompanied by more or less recrystallization. In by far most cases the foliation appears to have been produced under dynamic conditions, but recently some igneous rocks have been described as having had their foliation developed under mass-static conditions.[37] Here, again, we follow the suggestion of Gordon[38] and designate the most common of these rocks as granite-gneiss, diorite-gneiss, etcetera, thus clearly indicating the origin, structure, and composition of the rocks. Some amphibolites and some epidotite and chlorite schists, etcetera, also belong here. Since both ortho- and para-phyllites are really intermediate between megascopically non-crystalline foliates (slates), on the one hand, and gneisses and schists on the other, there is some doubt as to their exact position in the classification. Some phyllites are probably crystalline enough to warrant placing them with the gneisses and schists.

Ortho-slate and ortho-phyllite.—These rocks are megascopically non-crystalline, or only slightly crystalline, foliates which possess a more perfectly developed cleavage than the schists. They are produced essentially by pressure. As pointed out above, the phyllites, which are more crystalline than the slates, are really intermediate in structure between typical slates and typical schists.

NON-FOLIATES

The non-foliated metamorphic igneous rocks are produced essentially

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[34] C. H. Gordon: Bull. Geol. Soc. Am., vol. 7, p. 122.

[35] Adams and Barlow: Geol. Surv. Canada, Mem. 6, 1910, pp. 78-87.

[36] W. J. Miller: Jour. Geol., vol. 24, 1916, pp. 600-612.

[37] R. A. Daly: Geol. Surv. Canada, Transcontinental Guide Book 8, pt. 3, 1913, p. 130.

[38] C. H. Gordon: Bull. Geol. Soc. Am., vol. 7, p. 122.

- I. Meta-igneous Rocks.
  - Foliates.
    - 1. Primary ortho-foliates.
      - 1. Gneissoid granite.
      - 2. Gneissoid syenite.
      - 3. Gneissoid diorite.
      - 4. Gneissoid gabbro.
      - 5. Gneissoid peridotite.
      - 6. Gneissoid pyroxenite.
      - (etcetera.)
    - 2. Secondary ortho-gneisses and schists.
      - 1. Granite-gneiss and schist.
      - 2. Syenite-gneiss and schist.
      - 3. Diorite-gneiss and schist.
      - 4. Gabbro-gneiss and schist.
      - 5. Peridotite-gneiss and schist.
      - 6. Pyroxenite-gneiss and schist.
      - (etcetera.)
      - 7. Ortho-amphibolite.
      - 8. Some ortho-phyllite.
      - 9. Epidote and chlorite ortho-schists.
      - (etcetera.)
    - 3. Ortho-slate and most ortho-phyllite.
  - Non-foliates.
    - 1. Most serpentine.
    - 2. Most soapstone.
    - 3. Apobsidian.
    - 4. Aporhyolite.
    - 5. Apotrachyte.
    - 6. Apoandesite.
    - 7. Apobasalt.
    - (etcetera.)
- II. Meta-sedimentary Rocks.
  - Foliates.
    - 1. Para-gneisses and schists.
      - 1. Hornblende-quartz para-gneiss and schist.
      - 2. Hornblende-biotite para-gneiss and schist.
      - 3. Pyroxene-quartz para-gneiss and schist.
      - 4. Quartz-orthoclase para-gneiss and schist.
      - 5. Quartz-plagioclase para-gneiss and schist.
      - 6. Hornblende-orthoclase para-gneiss and schist.
      - 7. Quartz-biotite-orthoclase para-gneiss and schist.
      - (etcetera.)
      - 8 Conglomerate gneiss and schist.
      - 9. Impure marble gneiss and schist.
      - 10. Various para-schists—for example, chlorite, glaucophane, and epidote schists.
      - 11. Para-amphibolite, and eclogite.
      - 12. Some para-phyllite.
      - 13. Itabirite and jaspilite.
      - (etcetera.)
    - 2. Para-slate and most para-phyllite.
  - Non-foliates.
    - 1. Quartzite.
    - 2. Most marble.
    - 3. Some soapstone.
    - 4. Some serpentine.
    - 5. Hornfels.
    - 6. Anthracite.
    - 7. Some magnetite.
    - 8. Various contact metamorphic rocks.
    - (etcetera.)
- III. Injection Foliates.
  - 1. Injected ortho-gneisses and schists.
  - 2. Injected para-gneisses and schists.
- IV. Foliates of unknown Origin.
  - 1. Granitic gneiss and schist.
  - 2. Syenitic gneiss and schist.
  - 3. Dioritic gneiss and schist.
  - 4. Gabbroic gneiss and schist.
  - 5. Peridotitic gneiss and schist.
  - 6. Pyroxenitic gneiss and schist.
  - (etcetera.)
- V. Saprolites.
  - 1. Residual soils and subsoils.
  - 2. Laterites.
  - (etcetera.)

by chemical alteration under mass-static conditions. Thus most serpentines and soapstones are basic igneous rocks in which most of the minerals have altered to serpentine and talc respectively. Here belong also the various devitrified volcanic rocks which, following the proposal of Doctor Bascom,[39] are known as apobsidian, aporhyolite, etcetera. Other igneous rocks, chemically altered under mass-static conditions and designated by the prefix "apo," also belong in this category.

META-SEDIMENTARY ROCKS

FOLIATES

Para-gneisses and schists.—Rocks belonging to this important group of para-foliates are produced from strata essentially by pressure under either dynamic or mass-static conditions and usually with notable recrystallization. Except in a very few obvious cases—for example, conglomerate gneiss—the term "gneiss" or "schist" should be immediately preceded by the prefix "para-" to indicate derivation from a sedimentary rock, and this in turn by the names of the principal minerals contained. A great variety of schists and gneisses are to be thus classified, and in many cases there appears to be no satisfactory way of designating these except by long names.

Two important types of these para-gneisses and schists should be recognized: (1) dynamic para-gneisses and schists, which are sedimentary rocks with foliation developed essentially by compression accompanied by crystallization and usually with destruction of stratification, and (2) static para-gneisses and schists, which are sedimentary rocks whose foliation has been produced essentially by crystallization under mere downward pressure, due to load of overlying material, and often with more or less well preserved stratification. The writer is strongly of the opinion that static para-gneisses are much more common, especially among the very ancient rocks, than has been recognized. Such rocks have recently been described by Daly[40] in British Columbia and by the writer[41] in northern New York.

Para-slate and para-phyllite.—These are metamorphosed sediments, usually shales, with highly developed foliation produced under dynamic conditions, but with little or no megascopically evident crystallization. Thus their process of development and general appearance are much like those of the ortho-slate and ortho-phyllite, but they are notably more common than the latter. Since the para-phyllites exhibit all stages of transition between the true slates and the true schists, it becomes a matter of personal judgment as to how some of these should be classified. The writer believes that most of them should be classed with the slates.

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[39] F. Bascom: Bull. Geol. Soc. Am., vol. 11, 1900, pp. 121-122.

[40] R. A. Daly: Geol. Surv. Canada, Transcontinental Guide Book 8, pt. 2, 1913, pp. 131-132.

[41] W. J. Miller: Jour. Geol., vol. 24, 1916, pp. 588-600.

NON-FOLIATES

Some of the various rock types, like quartzite and most marble, which are classified under this heading, are of great importance. The various types are produced either by chemical alteration, crystallization, cementation, baking, contact metamorphism, or by a combination of two or more of these processes. Pressure is not essential to their origin, though much marble crystallizes under notable pressure without the development of foliation.

INJECTION FOLIATES

Practically all foliated rocks produced by either the "lit-par-lit" or the "mosaic" type of injection belong in this category. Both the intruded and the intrusive rock may possess foliation or only one may be foliated. Injection foliates always consist of at least two intimately associated rock-masses, and these may be wholly igneous, though they are usually foliated sediments injected with magmatic material, and hence intermediate.

FOLIATES OF UNKNOWN ORIGIN

In many districts certain or all of the foliates have not yet been definitely determined as to their igneous or sedimentary origin. A proper place should be left in the classification for such rocks, and descriptive, though genetically non-committal, names should be applied to them. Following the excellent suggestion of Gordon,[42] the writer would qualify such foliates by the use of the terms "granitic," "dioritic," etcetera, which suggest similarity to the general composition and appearance of ortho-foliates, but which are really non-committal as to their igneous or sedimentary origin. In some cases other terms not suggesting igneous rocks at all might be used.

SAPROLITES

The word "saprolite" literally means "rotten rock." It is an excellent term suggested by Becker[43] to include all residual products of the decay of rocks. In the broad sense of the term "metamorphism," the saprolites are metamorphic products, and they should be included in a classification of metamorphic rocks.

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[42] C. H. Gordon: Bull. Geol. Soc. Am., vol. 7, p. 122.

[43] G. F. Becker: U. S. Geol. Survey, 16th Ann. Rept., 1895, pt. 3, p. 289.

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WEATHERING OF ALLANITE[1]

BY THOMAS L. WATSON

(Presented before the Society December 28, 1916)

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[1] Manuscript received by the Secretary of the Society January 13, 1917.

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INTRODUCTION

Many observers, both in this country and abroad, have noted the alteration exteriorly of allanite to usually a reddish brown product whose general appearance on casual examination seemed to be closely similar. This alteration is frequently conspicuous in localities where allanite is found at or near the surface in lumps and masses, and is shown especially well at places in some of the Atlantic States, particularly in Virginia, in the Carolinas, in Pennsylvania, and in Texas, and in specimens examined by the writer from other localities in the United States and abroad.

Some of the more important localities have been studied in the field and collections made of the fresh allanite and its alteration product for laboratory study. During the progress of the investigation certain fundamental questions arose which the writer had assumed as settled, but which are now regarded by him to be at least doubtful. Chief among these is the composition of the ordinary so-called fresh, black, and vitreous allanite, which from preliminary work thus far accomplished suggests that it is a heterogeneous mixture and not a homogeneous compound. The problem, therefore, of allanite and its alteration can not be considered completed; but important results that are definite have followed from the investigation, which are set forth in this paper and will doubtless form the basis of future study.

During the progress of the laboratory investigation on this problem Mr. George L. English, of Rochester, New York, and Dr. D. F. Newland, Assistant State Geologist of New York, very kindly placed at the writer's disposal specimens of allanite from Pennsylvania and New York. Among the specimens donated by Mr. English were additional ones from localities in western North Carolina and from the new locality in Anderson County, South Carolina. The allanite from Chester County, Pennsylvania, and that from Ellenville, New York, exhibited the usual form of weathering. Analyses of the weathered product of the allanite from these localities could not be completed for this paper, but the results of the microscopic study are included. In each case the microscope showed similarity in the heterogeneous character of the weathered product.

While the results of microscopic study of the decomposed product of allanite are based on material from many widely separated localities in the eastern United States, chemical analyses are necessarily more restricted and are limited in this paper to unusually good material from several Virginia localities. After examination of similar material from other localities in the eastern United States and abroad, the Virginia material is considered to be representative for allanite weathering in general.

For the purposes of this paper and for future studies of allanite a careful search has been made of the literature relating to the occurrence and distribution of the mineral in the eastern United States and the results are briefly summarized herein.

Mode of Occurrence of Allanite

Our present knowledge of allanite indicates the principal conditions under which it is formed to be a constituent of (1) igneous rocks, (2) pegmatites, (3) contact metamorphism, and (4) dynamo-regional metamorphism.[2] Of these, the occurrence of allanite in pegmatites is the most important, since the mineral is usually developed in largest masses and in greatest quantity.

For many years allanite was regarded as a rare rock-forming mineral, but the investigations of Iddings and Cross[3] in 1885 demonstrated its wide distribution as a primary accessory constituent of many igneous rocks, in some of which it forms an important accessory mineral. Others have since extended the geographic distribution of allanite as a subordinate original constituent of igneous rocks, but have added little or nothing in the way of additional rock types. Localities in the United States where the mineral has been noted as a rock constituent are numerous and widely separated. When formed directly as a product from the consolidation of a molten magma, the mineral is almost invariably in small grains and crystals, frequently of microscopic dimensions only.

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[2] W. H. Emmons: Economic Geology, vol. iii, 1908, pp. 611-627.

[3] J. P. Iddings and W. Cross: Am. Jour. Sci., 3d ser., vol. xxx, 1885, pp. 108-111.

The principal occurrence of allanite in massive crystalline form of large but varying size and in more or less quantity is in pegmatite bodies of chiefly granitic composition. For those occurrences studied the mineral is regarded as an original constituent of the pegmatite. It is sometimes associated with epidote, and in 1890 Brögger[4] called attention to allanite-epidote intergrowths in certain pegmatites of Arendal, Norway, in which he regarded the allanite as primary. A similar association of allanite and epidote in igneous rocks has been reported by W. H. Hobbs,[5] F. D. Adams,[6] A. Lacroix,[7] G. H. Williams,[8] and others. The fresh and weathered allanite which forms the basis of this study was derived from pegmatitic occurrences in various localities in the Atlantic States.

The authentic occurrences of reported allanite in contact metamorphic deposits are apparently rare. Probably one of the best known examples is that described by Professor Emerson in Pelham, Massachusetts, where a macroscopic "reaction rim" was produced between a great dike of black olivine-enstatite rock and the inclosing gneiss. Professor Emerson says:[9]

> "Against the olivine rock is a broad band, characterized by very basic minerals—thick bands of biotite, containing apatite, and fine large corundum crystals. Then comes anorthite full of orthite, rutile, and corundum in large masses, etcetera.
>
> "A crystal of corundum was shown—largely fine blue sapphire, in which was a crystal of allanite a half inch across, which had coerced the corundum into a fine radiated puckering nearly an inch wide, outside of which the fine cleavage of the corundum asserted itself. The same puckering surrounds the allanite in the massive anorthite."

Allanite has been reported as a product of dynamo-regional metamorphism. According to Emmons and Calkins,[10] allanite is widely distributed in the rocks of the Philipsburg quadrangle, Montana, both as a pyrogenic and as a metamorphic mineral. It is an accessory in almost all the granular and porphyritic intrusives, and is very abundant in places in the marginal facies of some of the granitic batholiths at their contacts with sediments. It occurs partly in parallel intergrowths with pistacite, which always surrounds it, and the allanite is considered as probably primary.

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[4] W. C. Brögger: Zeitschr. fur Kryst., Bd. xvi, 1890, p. 99.

[5] W. H. Hobbs: Am. Jour. Sci., 3d ser., vol. xxxviii, 1889, pp. 223-228; Tschermak's Min. und Petrog. Mitth., Bd. xi, 1890, p. 1.

[6] F. D. Adams: Canadian Rec. Sci., vol. 4, 1891, p. 344.

[7] A. Lacroix: Bull. Soc. Min. de France, t. xii, 1889, pp. 138, 157, 210.

[8] G. H. Williams: Bull. 62, U. S. Geol. Survey, 1890.

[9] B. K. Emerson: Bull. Geol. Soc. Am., vol. 6, 1895, p. 474.

[10] W. H. Emmons and F. C. Calkins: Professional Paper 78, U. S. Geol. Survey, 1913, pp. 97, 159.

Distribution of Allanite in the eastern United States

NEW ENGLAND

General observations.—Allanite occurs in each of the New England States. It is quite widely distributed as a minor accessory mineral in the more acid igneous rocks, such as granite, as a constituent of pegmatites in several States, and as a contact metamorphic mineral in Pelham, Massachusetts. The mineral has been found at several localities in a partially decomposed or weathered state. The principal occurrences are briefly reviewed below by States.

Maine.—Although pegmatites of granitic composition in which feldspar quarries have been opened are fairly abundant over parts of south-central and southwestern Maine, allanite has been reported from only three localities. These are Mount Apatite, in the northern part of the town of Auburn, Androscoggin County; the town of Topsham, Sagadahoc County, and about Brunswick, where, according to Merrill,[11] "the variety orthite occurs in forms closely simulating rusty nails in the granitic rock about Brunswick."

The pegmatites at Mount Apatite are worked for feldspar, and to some extent for minerals as gems or as cabinet specimens. In addition to the rock minerals, feldspar (orthoclase, microcline, and albite var. cleve-landite), mica (muscovite, biotite, and lepidolite), and quartz, the other minerals reported are garnet, leucopyrite, tourmaline, beryl, apatite, allanite, amblygonite, autunite, cassiterite, columbite, cookeite, damourite, gummite, magnetite, molybdenite, triplite, and zircon.[12]

The list of reported minerals in the pegmatites of the town of Topsham is much smaller than for Mount Apatite. In addition to the rock minerals, the rarer ones include tourmaline, garnet, magnetite, columbite, beryl, gahnite, and allanite. Robinson[13] reported the occurrence of allanite in considerable abundance, and in the form of brownish crystals partially decomposed, resembling rusty nails driven into the granite. Analyses of the allanite[14] from this locality are given in the table on page 474.

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[11] G. P. Merrill: The Nonmetallic Minerals, John Wiley & Sons, New York, 1904, p. 201.

[12] G. F. Kunz: Am. Jour. Sci., 3d ser., vol. 27, 1884, pp. 303-305.
F. W. Clarke: Bull. 42, U. S. Geol. Survey, 1887, pp. 15-17.
S. L. Penfield: Am. Jour. Sci., 3d ser., vol. 47, 1894, p. 336.
J. E. Wolff and C. Palache: Proc Am. Acad. Arts and Sci., vol. 37, 1902, p. 515.
W. R. Wade: Eng. and Min. Jour., vol. 87, 1909, pp. 1127-1129.
E. S. Bastin: Bull. 420, U. S. Geol. Survey, 1910, pp. 23-26; Bull. 45, ibid., 1911, pp. 49-59.

Massachusetts.—In Massachusetts allanite occurs fairly well distributed as a constituent of certain igneous rocks, especially granite, and of some pegmatites. One of the most interesting occurrences of the mineral is at the asbestos mine at Pelham, where, according to Professor Emerson,[15] it is a constituent of the macroscopic "reaction rim" between the dike of black olivine-enstatite rock and the inclosing gneiss. Here it occurs abundantly in granular anorthite in crystals up to 2 inches long and one-half inch across. Professor Emerson has also recorded allanite from a number of localities in Hampshire and Franklin counties. It is a constituent of the Hatfield tonalite and of the Pelham gneiss, but the finest crystals are found at Gilbertville in coarse granite. At Buckland, south of the Harris soapstone quarry, allanite occurs superficially altered to a red substance. This is probably the alteration product of allanite due to weathering discussed for other localities in this paper.

Dale[16] reports allanite as an original accessory mineral in the granites of Quincy, Milford, Rockfort, and Becket, that of the Milford granite being rimmed in several instances with epidote. An interesting association is that of allanite with magnetite, ilmenite, epidote, zircon, fluorite, quartz, etcetera, in the ægerite and riebeckite pegmatite masses of the Quincy granite, the rare forms of amphibole and pyroxene being of unusual size.[17]

The occurrence of allanite in the granite of Essex County has been noted by Balch,[18] Iddings and Cross,[19] Sears,[20] and Washington,[21] and an analysis of the mineral from Swampscott[22] is given in column IV of table on page 474. Other occurrences of allanite[23] are at the Bolton quarry with petalite, etcetera, and in Athol on the road to Westminster in gneiss.

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[13] F. C. Robinson: Am. Jour. Sci., vol. 27, 1884, p. 412.

[14] F. C. Robinson: Am. Jour. Sci., vol. 27, 1884, p. 412.
F. W. Clarke: Am. Jour. Sci., vol. 28, 1884, p. 20.

[15] B. K. Emerson: Bull. 126, U. S. Geol. Survey, 1895, pp. 14-15; Bull. Geol. Soc. Am., vol. 6, 1895, p. 474; Mono. xxix, U. S. Geol. Survey, 1898, p. 754.

[16] T. N. Dale: Bull. 354, U. S. Geol. Survey, 1908.

[17] T. N. Dale: Ibid., 1908, p. 50.
C. H. Warren and C. Palache: Proc. Amer. Arts and Sci., 1911, pp. 125-168.

[18] D. M. Balch: Am. Jour. Sci., vol. 23, 1862, p. 348.

[19] J. P. Iddings and W. Cross: Am. Jour. Sci., vol. 30, 1885, pp. 108-111.

[20] J. H. Sears: Bull. Essex Inst., vol. 26, 1894, p. 189.

[21] H. S. Washington: Jour. Geology, vol. 6, 1898, pp. 787-808; see especially pp. 792-793.

[22] D. M. Balch: Loc. cit., p. 348.

Prof. A. C. Lane, of Tufts College, who kindly sent the writer notes on the occurrence of allanite in Essex County, accompanied by specimens, states that the mineral is found in the quarries of the Winchester Rock and Brick Company on Blueberry Mountain and the Fessenden Road quarry in Arlington. The allanite occurs in "granodiorite aplites" or pegmatites associated with feldspar chiefly plagioclase, chlorite, both massive and thin folia, replacing biotite, epidote, pyrite, and magnetite. The largest lump of allanite observed was 2 to 3 centimeters in diameter. Lane adds that the allanite acts as a center of crystallization for the feldspar and is not infrequently surrounded by a rusty zone of the altered mineral.

New Hampshire and Vermont.—Dale[24] reports allanite as a subordinate original accessory constituent in the granites of Milford, Kilkenny, Conway, and Redstone, New Hampshire, and of Caledonia, Orange, Orleans, Washington, and Windsor counties, Vermont. The pegmatite of Milford, New Hampshire, contains accessory allanite associated with magnetite and zircon.[25]

Connecticut and Rhode Island.—Allanite as a minor primary accessory mineral in the granites of Connecticut and Rhode Island, especially those of the Westerly and Niantic quarries, has been reported by many observers.[26] According to Professors Rice and Gregory,[27] the occurrence of small spots of allanite in the Westerly quarries has given the rock the local name of "bed bug granite." Dana[28] lists allanite at Allen's vein at the gneiss quarries in Haddam.

MIDDLE ATLANTIC STATES

General observations.—The chief occurrence of allanite in these States is in pegmatite bodies, which carry in several instances a long and interesting list of associated rarer minerals. At some of the localities the crystalline masses of allanite exhibit the usual reddish brown alteration product from weathering.

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[23] E. S. Dana: A System of Mineralogy, 1900, p. 525.

[24] T. N. Dale: Bull. 354, U. S. Geol. Survey, 1908; ibid., 404, 1909; ibid., 430, 1910, pp. 346-372.

[25] T. N. Dale: Bull. 354, U. S. Geol. Survey, 1908, p. 48.

[26] J. P. Iddings and W. Cross: Am. Jour. Sci., vol. 30, 1885, p. 108.
J. F. Kemp: Bull. Geol Soc. Am., vol. 10, 1899, p. 368.
T. N. Dale: Bull. 354, U. S. Geol. Survey, 1908, pp. 194-204, 205, 207.

[27] W. N. Rice and H. E. Gregory: Bull. No. 6, Conn. Geol. and Nat. Hist. Survey, 1906, p. 154.

[28] E. S. Dana: A System of Mineralogy, 1900, p. 525.

New York.—Of the large number of interesting minerals found in the pegmatites of Port Henry and vicinity, Essex County, New York, allanite has been reported in unusual amount and in crystals of exceptional size and perfection.[29] In a coarse pegmatite which accompanies the magnetite at the Smith mine, Mineville, more particularly in the Cook shaft, allanite occurs at times in great abundance, and, according to Kemp,[30] is richly disseminated in irregular crystals up to the size of one's hand. Newland states[31] that at one time there was a large accumulation of waste rock on the ground from which allanite could be obtained in specimens up to several pounds in weight, and mentions one large piece of probably 15 or 20 pounds weight which he obtained several years ago.

Some fine specimens of allanite have come from the Sanford ore bed (now called "Old Bed" mine), 2 miles south of the Smith mine, where the occurrence has been described by W. P. Blake[32] and E. S. Dana.[33] Crystals 8 or 10 inches long, 6 or 8 inches broad, and 1 to 2 inches thick are mentioned. The mineral is no longer available.

Kemp gives a large list of interesting minerals in the pegmatites of the Elizabethtown and Port Henry quadrangles. These are allanite, apatite, amphibole, albite, arsenopyrite, biotite, fluorite, garnet, lanthanite, magnetite, molybdenite, pyrite, pyroxenite, quartz, titanite, wernerite, and zircon.[34]

At Mounts Adam and Eve, Warwick, Orange County, Kemp[35] reports allanite as "frequent in the granite from the quarries on Adam and Eve, and also in especially large amount in rather coarse pegmatitic masses of feldspar and quartz, that occur in the stone, etcetera." The allanite is found in crystals and masses and is extremely brittle. In sections the mineral is yellowish brown to seal brown, and, as usual, is strongly pleochroic. It is accompanied by purple fluorspar, which appears along the edges of the crystals. It is also said to be bounded at times "by a lighter colored brown rim of what is probably slightly decomposed allanite. The optical properties of the Edenville allanite have been measured by Michel-Levy and Lacroix, who determined the mean index of refraction to be above 1.78, and the difference between the greatest and least indices to be 0.032."[36]

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[29] J. F. Kemp and R. Ruedemann: Museum Bulletin 138, N. Y. State Museum, 1910, pp. 125, 126, 153-154.
J. F. Kemp: Trans. Am. Inst. Min. Engrs., vol. 27, 1897, p. 195.
J. F. Kemp: Am. Jour. Sci., vol. 40, 1890, p. 62.
H. Ries: Trans. N. Y. Acad. Sci., vol. 16, 1897, pp. 327-329.

[30] J. F. Kemp: Op. cit., 1910, p. 154.

[31] D. H. Newland: Personal communication, September 25, 1916.

[32] W. P. Blake: Am. Jour. Sci., vol. xxv, 1858, p. 259; ibid., vol. 26, 1858, p. 346.

[33] E. S. Dana: Am. Jour. Sci., vol. xxviii, 1884, p. 479; Groth's Zeitschr., Bd. 9, p. 283.

[34] J. F. Kemp: Op. cit., 1910, p. 153.

[35] J. F. Kemp: N. Y. Acad. Sci., vol. vii, 1892-1894, pp. 638-650.

Bastin[37] mentions the occurrence of allanite in the pegmatite at Crown Point, but the mineral is probably very sparsely distributed. Allanite is also found in the pegmatite at Edenville,[38] near Warwick, and as tabular crystals at West Point,[39] in Orange County, and in pegmatite at Ellenville,[40] Ulster County. The allanite from the Ulster County locality exhibits some exterior alteration from weathering.

Although found in many localities in New York State, the only published analyses of allanite known to the writer are of the mineral from West Point and Monroe, Orange County (analyses III and VII of table on page 474.

New Jersey.—Tabular crystals of allanite up to 3 inches across and of dull black color are reported to be abundant in the coarse granite of the Trotter mine, Franklin furnace, and in the same rock in various iron (magnetite) mines.[41] According to Kemp,[42] allanite is very abundant in the granite dike that pierces the ore body of the Trotter mine, and in pegmatite masses in the abandoned iron mines on the hill north of the depot. It also occurs with pyroxene in the Mud mine at Ogdensburg, where the granitic or dioritic intrusions are well developed. Palache[43] mentions the following minerals associated with allanite in the magnetite near Franklin furnace: Arsenopyrite, phlogopite, rutile, scapolite, iron spinel, and zircon. Some of these he says are directly traceable to the granite associated with the ores. Bayley[44] remarks that most of the minerals named are probably in the ore within the limestone.

Pennsylvania.[44a]—Allanite occurrences in Pennsylvania are limited to Northampton, Lehigh, Berks, Bucks, Montgomery, Chester, Delaware, and Philadelphia counties, in the southeastern part of the State. It is found chiefly as crystals and crystalline masses in pegmatite dikes, associated with mica, ilmenite, zircon, and a variety of other accessory minerals, chiefly the rare earths.[45] Analyses V, VI, VIII, and IX of table on page 474 are of allanite from different localities in Pennsylvania.

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[36] Bull. Soc. Min. Trans., vol. xi, 1888, p. 65.

[37] E. S. Bastin: Bull. 420, U. S. Geol. Survey, 1910, p. 55.

[38] E. S. Dana: A System of Mineralogy, 1892, p. 525.

[39] C. Bergemann: Am. Jour. Sci., vol. 13, 1852, p. 416.
H. P. Whitlock: Bull. 70, N. Y. State Museum, 1903, p. 56.

[40] Specimen kindly furnished the writer by Mr. George L. English, Rochester, New York.
C. Bergemann: Pogg. Ann., Bd. 84, p. 485.
Genth and Keyser: Am. Jour. Sci., vol. 19, 1855, p. 20.
Erdm. Jour. Pract. Chem., Bd. 64, p. 471.
Reakirt: Jour. pr. Chem., Bd. 60, p. 274.

[41] Franklin Furnace folio, New Jersey, No. 161, 1908, p. 8.

[42] J. F. Kemp: N. Y. Acad. Sci., vol. vii, 1892-1894, pp. 638-650.

[43] Franklin Furnace folio, New Jersey, No. 161, 1908, pp. 8-10.
A. S. Eakle: Trans. N. Y. Acad. Sci., vol. xiii, 1894, pp. 102-107; Am. Jour. Sci., vol. xlvii, 1894, pp. 436-439.
T. S. Hunt: Am. Jour. Sci., vol. 34, 1862, p. 204.

[44] W. S. Bayley: Geol. Survey of New Jersey, vol. vii, 1910, p. 116.

[44a] The writer makes grateful acknowledgment to Dr. Edgar T. Wherry, U. S. National Museum, for much of the data relating to allanite in Pennsylvania.

Along the belt of Precambrian rocks extending through Northampton, Lehigh, and Berks counties, allanite[45a] is of common occurrence as a constituent of pegmatite, in much of which it is the only accessory mineral. The grains are usually only a few millimeters in diameter, but locally attaining 30 or 40 centimeters. The most important localities in this region are: One mile south of Redington, Lower Saucon township, Northampton County (the source of material analyzed from "Bethlehem," Pennsylvania); South Mountain, south of South Bethlehem, where a mass weighing 100 pounds was obtained; Colesville, Lehigh County, where a large specimen of lanthanite was at one time found, resulting from the decomposition of the allanite; Pricetown, Berks County, where it is associated with ilmenite, and McKnights Gap, northeast of Reading, Berks County, where large masses have recently been obtained.

The pegmatites of the southeastern belt of Precambrian rocks, which extends from Bucks to Chester counties and through the northern part of the city of Philadelphia, also contain allanite occasionally, but it is here usually associated with a variety of other accessory minerals. Important localities are: Hoffmans quarry, Frankford, Philadelphia, where it is associated with scheelite; Johnsons quarry, Morton, Delaware County, where euxenite, columbite, and other rare earth minerals accompany it, and East Bradford township, Chester County, where it is not found in place, but is plowed up in the fields, and is accordingly more extensively weathered than in most other occurrences.

Specimens of massive allanite from East Bradford, Chester County, recently donated the writer by Mr. George L. English, are entirely covered by a crust of the altered mineral derived from weathering. The allanite is intergrown with quartz and is altered to the usual reddish brown crust with, in places, an outer thin layer of yellow brown to buff in color. The powder is soluble in hot dilute HCl, yielding some gelatinous silica; is infusible before the blow-pipe, becoming magnetic; yields water in closed tube when heated, which reacts neutral; and does not react for carbonates. The weathered product was studied microscopically and found to be heterogeneous, in common with that from other localities, composed of both crystalline and isotropic grains each having variable properties.

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[45] The following references refer chiefly to analyses:
E. S. Dana: A System of Mineralogy, 1900, p. 525.
C. Hintze: Handbuch der Mineralogie, 1897, pp. 269-270.
F. H. Genth: Am. Jour. Sci., vol. 19, 1855, p. 20.
C. F. Rammelsberg: Pogg. Ann., Bd. 80, p. 285.
Nils Engström: Groth's Zeitschr., Bd. 3, p. 194.

[45a] The references here given refer to descriptions of occurrences of allanite:

F. A. Genth: Mineralogy of Pennsylvania, Rept. B, Second Geol. Survey Pa., 1874, pp. 79-80.

John Eyerman: Mineralogy of Pennsylvania, Private Publications, pt. i, 1889, p. 20; pt. ii, 1911, p. 10.

Edgar T. Wherry: Radioactive minerals found in Pennsylvania. Jour. Franklin Institute, vol. 165, 1908, pp. 67, 70, and 75-78.

Elmer Benge and Edgar T. Wherry: Directory of the mineral localities in and around Philadelphia. Mineral Collector, vols. 12-15, 1905-1908; numerous mentions of allanite.

ANALYSES OF ALLANITE FROM THE NEW ENGLAND AND MIDDLE ATLANTIC STATES

While the nine analyses of allanite tabulated below from the New England and Middle Atlantic States are lacking in some cases in completeness and otherwise are unsatisfactory, they will illustrate in a general way the wide variation in the composition of the mineral—an important feature discussed elsewhere in this paper. A second noteworthy feature is the absence of the yttria earths from seven of the nine analyses, amounting to less than 2 per cent in each of the two in which they are reported. These analyses should be compared with those from Virginia and North Carolina on page 479.

Analyses of Maine-Massachusetts-New York-Pennsylvania Allanite

	I	II	III	IV	V	VI	VII	VIII	IX
SiO_2	37.20	34.97	33.83	33.31	33.31	32.89	32.19	31.86	31.56
Al_2O_3	10.24	12.83	13.61	14.73	14.34	12.49	12.00	16.87	16.77
Fe_2O_3	.....	.....	3.33	.....	10.83	7.33	6.34	3.58	5.74
Ce_2O_3	8.66	17.26	20.90	21.94	13.42	15.68	15.37	21.27	18.15
Di_2O_3	9.57	.....	.....	.....	.....	.....	.....	.....	2.71
La_2O_3	.....	.....	.....	.....	2.70	10.10	8.84	2.40	
Y_2O_3	.....	.....	.....	1.32	.....	.....	.....	.....	1.65
ThO	.....	.....	.....	.....	.....	.....	.....	.....	0.31
FeO	24.46	18.11	12.72	15.82	7.20	9.02	10.55	12.26	9.08
MnO	.....	2.82	0.82	.....	.....	0.25	0.51	.....	1.15
MgO	.....	1.40	1.40	1.25	1.23	1.77	0.84	1.67	.....
CaO	6.84	7.21	9.36	7.85	11.28	7.12	9.14	10.15	9.35
Na_2O	1.26	.....	.....	.....	0.41	0.09	1.00	.....	.....
K_2O	.....	.....	.....	.....	1.33	0.14	0.18	.....	0.37
H_2O	1.74	4.13	2.95	1.49	3.01	2.49	1.19	1.11	2.25
	99.97	98.73	98.92	97.71	99.06	99.37	98.15	101.17	99.09

I. Allanite from Topsham, Maine. J. Torrey, Jr., analyst. F. C. Robinson: American Journal of Science, volume 27, 1884, page 412.

II. Allanite from Topsham, Maine. Clarke: American Journal of Science, volume 28, 1884, page 20.

III. Allanite from West Point, New York. Bergemann: Pogg. Ann., Bd. 84, page 485.

IV. Allanite from Swampscott, Massachusetts. Balch: American Journal of Science, volume 33, 1862, page 348.

V. Allanite from near Bethlehem, in Northampton County, Pennsylvania. Genth and Keyser: American Journal of Science, volume 19, 1855, page 20.

VI. Allanite from Berks County, Pennsylvania. Genth and Keyser: American Journal of Science, volume 19, 1855, page 20.

VII. Allanite from near Monroe, Orange County, New York. Genth and Keyser: American Journal of Science, volume 19, 1855, page 20. Erd. Journ. pr. Chem., Bd. 64, page 471; Reakirt: Journ. pr. Chem., Bd. 60, page 274.

VIII. Allanite from East Bradford, Chester County, Pennsylvania. Rammelsberg: Pogg. Ann., Bd. 80, page 285.

IX. Allanite from East Bradford, Chester County, Pennsylvania. Engström: Groth's Zeitschr., Bd. 3, page 194.

SOUTH ATLANTIC STATES

General observations.—In the South Atlantic States, allanite occurs as parallel intergrowths with epidote in the granites of Maryland, and as a constituent of pegmatites associated with a variety of other less common minerals in Virginia and the Carolinas. At many localities in these States, especially in Virginia, and to a less extent in the Carolinas, the mineral is found in quantity in crystalline lumps and masses, coated by a reddish brown crust when found above local ground water level, that affords excellent material for the study of allanite weathering.

Maryland.—The occurrence of allanite in Maryland is as a microscopic accessory rock-forming mineral in the granites of Ilchester, Dorsey Run Station, Woodstock, on Gunpowder River, and to the northeast of Baltimore.[46] In each of these localities allanite is intimately associated with epidote as parallel intergrowths,[47] and has been generally regarded as an original magmatic mineral. Allanite has not been reported as a constituent in any of the pegmatites of Maryland, although they have been worked in a number of localities.

Virginia.—Pegmatites occur in many of the Virginia Piedmont counties, some of which are allanite bearing. The mineral is known to occur in at least seven counties in the crystalline province of the State (map, figure 1). These are Amelia County, in the middle eastern part of the Piedmont Plateau, and Amherst, Bedford, Fauquier, Nelson, Page, and Roanoke counties, each of which lies partly in the Blue Ridge Mountains. In addition to these, the writer has examined specimens of allanite reported to have come from Franklin and Patrick counties. It is found in considerable quantity in several of the Blue Ridge Mountains localities, probably the most notable one of which is on Little Friar Mountain, in Amherst County, where the allanite is associated with magnetite and the very rare mineral sipylite.[48]. With only one exception (Amelia County), the Virginia localities have yielded crystalline masses of the mineral incrusted by its alteration product nowhere excelled, so far as the writer is aware, for chemical and microscopic investigation of allanite weathering.

In the pegmatites[49] of the Amelia County area the associates of allanite,

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[46] C. R. Keyes: 15th Ann. Rept., U. S. Geol. Survey, 1893-1894, pp. 704-710.

[47] W. H. Hobbs: Johns Hopkins Univ. Circulars, 1888, No. 65, p. 69; Am. Jour. Sci., vol. 38, 1889, pp. 223-228; Tschermak's Min. u. Pet. Mitth., vol. xi, 1889, p. 1; American Geologist, vol. 12, 1893, pp. 218-219.

C. R. Keyes: Bull. Geol. Soc. Am., vol. 4, 1892-1893, pp. 305-312.

[48] J. W. Mallet: Am. Jour. Sci., vol. 14, 1877, p. 397.

[49] W. M. Fontaine: Am. Jour. Sci., vol. 25, 1883, pp. 330-339.

Thomes L. Watson: Mineral resources of Virginia, 1907, pp. 280-283; Bull. Am. Inst. Mng. Engrs., 1916, pp. 1237-1243.

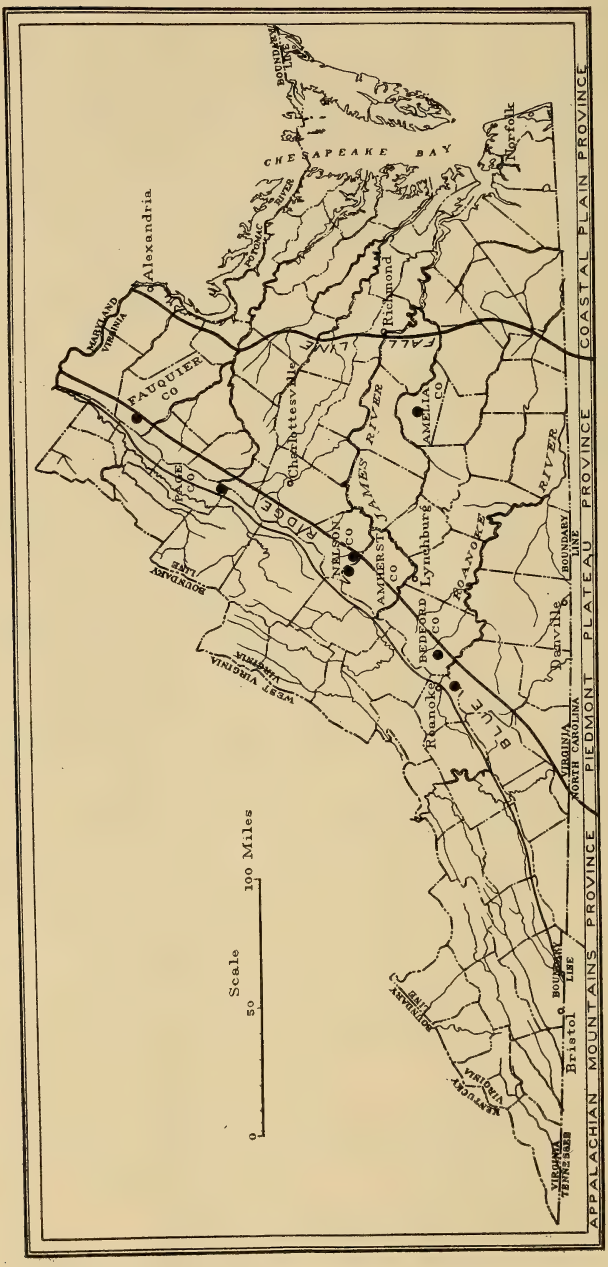
Alexandria
MARYLAND
VIRGINIA
BOUNDARY LINE
POTOMAC RIVER
CHESAPEAKE BAY
Norfolk
Richmond
FALL LINE
FAUQUIER CO
PAGE CO
Charlottesville
JAMES RIVER
AMELIA CO
NELSON CO
AMHERST CO
Lynchburg
ROANOKE RIVER
BEDFORD CO
Roanoke
Danville
BLUE RIDGE
BOUNDARY LINE
WEST VIRGINIA
VIRGINIA
BOUNDARY LINE
Scale
0
50
100 Miles
BOUNDARY LINE
Bristol
KENTUCKY
VIRGINIA
VIRGINIA
TENNESSEE
VIRGINIA
NORTH CAROLINA
BOUNDARY LINE
APPALACHIAN MOUNTAINS PROVINCE
PIEDMONT PLATEAU PROVINCE
COASTAL PLAIN PROVINCE

FIGURE 1.—*Outline Map of Virginia, showing Allanite Localities*

in addition to the common rock-forming silicate minerals, are fluorite, garnet, tourmaline, beryl, helvite, zircon, columbite, microlite, apatite, and monazite. Except fluorite, tourmaline, and zircon, analyses have been made of each of these minerals, including allanite.[50]

About 3 miles southeast of Marksville, Page County,[51] black vitreous allanite occurs in pegmatite cutting quartz-bearing hypersthene syenite and is associated with titaniferous magnetite. The mineral weathers exteriorly to the usual reddish brown crust coated by a thin outer light-colored layer of the weathered mineral.

North Carolina.[52]—Many of the numerous pegmatite dikes of western North Carolina have been long and favorably known for the variety of rare minerals which they contain. There are known at present more than 40 minerals from the pegmatites of this State.

In western North Carolina allanite has been noted as a constituent in the pegmatites of many counties, especially Alexander, Buncombe, Henderson, Iredell, Madison, and Mitchell, probably the largest number of localities for any single State. In most of these the mineral occurs very sparingly as a minor constituent, but in several it is found in quantity. Black or brownish black slender crystals up to 6 and 12 inches long have been found in the pegmatite at Balsam Gap, Buncombe County, and near Bethany Church, in Iredell County, allanite is found in massive form and in large quantity like that in Amherst County, Virginia. Small crystals of zircon are imbedded in the allanite of Iredell County. When found above water level the allanite exhibits exteriorly alteration from weathering to a reddish brown crust.

South Carolina.—To the writer's knowledge the only known occurrence of allanite in South Carolina is 4½ miles east of Iva, Anderson County.[53] The allanite comes from a shallow opening made for gold in a very coarse pegmatite composed chiefly of grayish quartz, with a little mica and not very much feldspar. From the same opening were derived pyroxmangite (manganese pyroxene), a new member of the pyroxene group, and its alteration product, skemmatite, a black oxide of iron and manganese, recently described by Ford and Bradley.[54] Scattered over the surface in the immediate vicinity of the hole are pieces of an unknown mineral, probably an altered pyroxene, ranging in size from small fragments up to masses probably 50 pounds in weight. Several hundred yards to the south are found zircon crystals, good cleavage fragments of corundum, and limonite pseudomorphs after pyrite.

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[50] J. A. Cabell: Chemical News, vol. xxx, 1874, p. 141.
W. T. Page: Chemical News, vol. 38, 1878, p. 94; ibid., vol. 46, 1882, p. 195.
F. P. Dunnington: Am. Chem. Jour., vol. 4, 1882, p. 138.
George A. Koenig: Proc. Acad. Philadelphia, 1882, p. 103.
W. M. Fontaine: Am. Jour. Sci., vol. 25, 1883, pp. 330-339.
C. C. Memminger: Am. Chem. Jour., vol. 6, 1885, p. 172.
W. G. Brown: Am. Chem. Jour., vol. 6, 1885, p. 172.
Thomas L. Watson: Bull. Am. Inst. Mng. Engrs., 1916, pp. 1240-1241.

[51] E. S. Larsen: Personal communication, December, 1916.

[52] F. H. Genth and W. C. Kerr: The Minerals and Mineral Localities of North Carolina, Raleigh, 1885, pp. 50-51.
J. H. Pratt: Economic Paper No. 6, North Carolina Geol. Survey, 1902, pp. 40-58.
D. B. Sterrett: U. S. Geol. Survey, Bull. 315, 1906, pp. 400-422; ibid., Bull. 430, 1910, pp. 593-638.
See other publications of the North Carolina Geol. Survey, especially the Economic Papers, and the annual volumes of Mineral Resources of the United States published by the U. S. Geol. Survey.
W. E. Hidden: Am. Jour. Sci., vol. 22, 1881, p. 21; ibid., vol. 24, 1882, p. 372.
J. W. Mallet: Chem. News, vol. 44, 1881, p. 215.
F. H. Genth: Am. Philos. Soc., 1882, Aug. 18; ibid., 1887, March 18.

The black, vitreous mass of allanite from this locality exhibits the usual deep reddish brown crust derived from the fresh mineral by weathering and has afforded excellent material for study. The powder is soluble in hot dilute HCl with the separation of gelatinous silica; is infusible before the blow-pipe and non-magnetic; yields water when heated in closed tube which reacts neutral; and does not react for carbonates.

ANALYSES OF ALLANITE FROM VIRGINIA AND NORTH CAROLINA

For purposes of comparison eight analyses of allanite from different localities in Virginia and North Carolina are tabulated below in order of decreasing silica. Attention need only be directed in the analyses to the following features in the composition of the mineral from these States: (1) Predominance of ceria over the oxides of the other metals (lanthanum and didymium) belonging to the cerium group in six of the analyses with didymia in largest amount in analyses I and V. (2) Absence of the metals of the yttrium group in four (Virginia) of the eight analyses and the presence of these in each of the three analyses of the North Carolina mineral, ranging in amount up to nearly 2 per cent (I). Unusual richness of analysis VIII (Virginia) in the oxides of the cerium metals (51.13 per cent, more than double the usual amount), especially in ceric oxide (33.76 per cent), which are the maxima for any analysis of the mineral yet recorded. When compared with the other eighty-four analyses of allanite listed by Hintze,[55] the Virginia mineral (VIII) contains nearly 6 per cent more of ceric oxide than the maximum one (28.19

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[53] The locality is a new one for allanite. It was visited about five years ago by Mr. George L. English, of Rochester, New York, who first identified the mineral as allanite, and who recently very kindly placed an excellent specimen of it at the writer's disposal. The writer makes further grateful acknowledgment to Mr. English for some unpublished notes on the locality on which the above statement is based.

[54] W. E. Ford and J. H. Bradley: Am. Jour. Sci., vol. xxxvi, 1913, pp. 169-174.

[55] C. Hintze: Handbuch der Mineralogie, 1897, pp. 272-276.

per cent) recorded. A second noteworthy feature of the analysis is the large quantity of didymia as compared with lanthana.

Analyses of Virginia-North Carolina Allanite

	I	II	III	IV	V	VI	VII[56]	VIII
SiO_2	32.79	32.35	32.05	31.71	31.68	31.23	30.04	26.70
TiO_2	.....	.....	.....	.86	.....	.....	.....	.....
Al_2O_3	18.16	16.42	22.93	9.32	17.33	16.45	16.10	6.34
Fe_2O_3	1.64	4.49	11.04	11.95	7.05	3.49	5.06	3.21
Ce_2O_3	6.07	11.14		13.90		11.24	11.61	33.76
Di_2O_3	14.40	6.91	14.81	9.07	18.99[57]	9.90	5.39	16.34
La_2O_3	.....	3.47		1.25			4.11	1.03
Er_2O_3	.....	.....	.....	none	1.12	.....	.....	.52
Y_2O_3	1.84	.....	0.85	none		1.65	.....	.....
FeO	10.08	10.48	.....	8.95	10.11	13.67	9.89	4.76
BeO	.....	.....	.....	.....	.....	.24	.....	.....
MnO	1.23	1.12	1.99	.18	1.03	.....	trace	trace
CaO	10.95	11.47	9.43	11.02	10.79	8.69	13.02	2.80
MgO	0.15	.....	1.28	.96	0.54	.22	1.11	.54
Na_2O	0.33	.46	0.54	.16	0.21	.....	.28	.49
K_2O	0.12		0.20		trace	.....	.02	.55
H_2O	1.89	2.31	3.64	.86	1.46	2.28	2.56	1.99
	99.65	100.62	98.76	100.19	100.31	99.06	99.36	99.03
Sp. gr.	3.40	3.323	3.005	3.64	3.63	3.83	3.59	4.32

I. Allanite from Balsam Gap, Buncombe County, North Carolina. F. A. Genth, Mineralogy of North Carolina, 1881, page 45.

II. Allanite from near Amelia Courthouse, Amelia County, Virginia. F. P. Dunnington, American Chemical Journal, volume 4, 1882, page 138. For a second and less complete analysis, see Koenig, Proceedings of the Academy of Philadelphia, 1882, page 103.

III. Allanite from hiddenite mine near Hiddenite, Alexander County, North Carolina. F. A. Genth, American Philosophical Society, volume 20, 1882, page 402.

IV. Allanite from crest of Blue Ridge Mountains 9 miles south of Roanoke, Roanoke County, Virginia, within a few paces of the Franklin County line. S. D. Gooch, analyst.

V. Allanite from near Bethany Church, Iredell County, North Carolina. H. F. Keller, American Philosophical Society, volume 24, 1887, page 42.

VI. Allanite from Little Friar Mountain, Amherst County, Virginia. J. A. Cabell, Chemical News, volume xxx, 1874, page 141.

VII. Allanite from near Lowesville, Nelson County, Virginia. C. G. Memminger, American Chemical Journal, volume 7, 1885-1886, page 177.

VIII. Allanite from Bedford County, Virginia. W. T. Page, Chemical News, volume 46, 1882, page 195.

GULF STATES

General observations.—Thus far Texas is the only one of the Gulf States in which allanite is known to occur.

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[56] Includes SnO_2, .17 per cent.

[57] Mostly Di_2O_3; 5 per cent Ce_2O_3.

Texas.—In the famous giant pegmatite forming Baringer Hill,[58] Llano County, Texas, allanite is reported to occur in masses weighing up to 300 pounds, imbedded in purple fluorspar, and is associated among other minerals with a variety of rare earth ones in unusually large masses and quantities. In addition to allanite are found other minerals containing yttria and its companions, such as gadolinite, yttrialite, thorogummite, nivenite, fergusonite, tengerite, cyrtolite, rowlandite, mackintoshite, and yttrocrasite. Several of these are peculiar to this locality. Gadolinite, the chief source of the yttria earths, occurs in crystals and masses of irregular shape up to 200 pounds in weight.

Hess reports the excavations thus far made to be comparatively shallow and the minerals found to be more or less weathered. Allanite exhibits weathering around the edges and along cracks to the usual reddish brown product, which is well shown by a specimen of the fresh dense black and vitreous mineral from this locality in the collections of the United States National Museum.

COMPOSITION OF ALLANITE

GENERAL OBSERVATIONS

Examination of the 85 analyses of allanite listed by Hintze[59] from all parts of the world shows the widest possible variation both in composition and in specific gravity. (See analyses of allanite from the Atlantic States, tabulated on pages 474 and 479.) Some of the analyses show considerable water, which is probably due to alteration. Most of the analyses were made many years ago, some are less complete than others, and none can be counted as modern. Again, the degree of purity in each case of the sample analyzed is unknown. To these facts must be accorded some weight in accounting for the variation in composition, but to what extent it is not possible to state.

It is believed that the chief cause for variation in the composition of allanite is to be attributed to the heterogeneous nature of the mineral. Recent microscopic study by Dr. E. S. Larsen, United States Geological Survey, of five specimens of black, vitreous, and supposedly fresh allanite from as many different localities demonstrates its heterogeneous character and leads to the conclusion that for the localities examined at least allanite is made up of two and probably three distinct minerals. Dr. Larsen's results, which, with his permission, are published here for the first time, follow:

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[58] Frank L. Hess: U. S. Geol. Survey, Bull. 340, 1908, pp. 286-294.
W. E. Hidden and J. B. Mackintosh: Am. Jour. Sci., vol. 38, 1889, p. 474.
W. E. Hidden: Am. Jour. Sci., vol. 42, 1891, p. 430; ibid., vol. 19, 1905, p. 425.
W. E. Hidden and W. F. Hillebrand: Am. Jour. Sci., vol. 46, 1893, pp. 98, 208.
W. F. Hillebrand: Am. Jour. Sci., vol. 13, 1902, p. 145.
W. E. Hidden and C. H. Warren: Am. Jour. Sci., vol. 22, 1906, p. 515.

[59] C. Hintze: Handbuch der Mineralogie, 1897, pp. 272-276.

ROANOKE COUNTY, VIRGINIA [60]

A microscopic study of the black, vitreous allanite, from what appeared to be the freshest part of the specimen, showed that it is made up of two different minerals—a pale olive green, sensibly isotropic mineral, and a pale green, birefracting mineral. The birefracting mineral is derived from the sensibly isotropic mineral and replaces it along streaks and irregularly. (A thin-section would show this better.)

The isotrophic mineral has an index of refraction of about 1.697 ± .003. The birefracting mineral is faintly pleochroic with $x =$ pale green and $z =$ yellowish. The mean index of refraction is about 1.71 and the birefringence is about 0.01.

AMHERST COUNTY, VIRGINIA [61]

All of the material examined is birefracting. It is probably optically negative (—), with a large axial angle, but no good interference figure was had, probably owing to some abnormal dispersion. $\beta = 1.755$, varies 0.01. Birefringence = 0.01 about; $x =$ pale yellowish, $z =$ deep reddish brown.

ALBANY, WYOMING [62]

The blackish brown, vitreous material is made up of two or probably three distinct minerals. Thin sections show the relations clearly. A nearly colorless, isotropic mineral is replaced in irregular areas by a pale greenish, faintly birefracting mineral, and these two are in turn altered along the borders of the grains and along cracks and streaks to a reddish brown, rather strongly birefracting mineral. This latter makes up over half of the sections of the large piece and all but a small core of the small grains—up to several millimeters across. The alterations suggest the alteration of olivine to iddingsite, and in both the oxidation of iron is probably an important change.

(*a*) The colorless to pale greenish, isotropic mineral has a rather constant index of refraction of 1.685 ± 0.005.

(*b*) The pale green, birefracting mineral has a somewhat higher index of refraction and a weak birefringence. It is pleochroic with $x =$ nearly colorless and $z =$ pale green.

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[60] T. L. Watson.

[61] F. L. Hess.

[62] F. L. Hess.

(*c*) The reddish brown mineral has the following optical properties, which vary a little: Optically negative (—), 2V = rather large, $\delta > V$ rather strong.

$\alpha = 1.727 \pm 0.005$, X = pale yellowish.
$\beta = 1.739 \pm 0.005$, Y = reddish brown.
$\gamma = 1.749 \pm 0.005$, Z = reddish brown.

Evidently the "allanite" of these specimens is made up of at least two and probably three distinct minerals. The one is pale colored, sensibly isotropic, and has an index of refraction of about 1.68 to 1.70; another, possibly related to the former, has a somewhat higher index of refraction, a weak birefringence, and is pleochroic in green and yellow. The third is clearly derived from the others and has the following optical properties: Optically negative (—), 2V = rather large, $\delta > V$ rather strong. $\beta = 1.71$ to 1.76. Birefringence, 0.01 to 0.02. Pleochroic in red brown with absorption Y and Z > X.

LLANO COUNTY, TEXAS[63]

In mass, black and vitreous; in thin section rather deep olive green. Isotropic and nearly homogeneous. $n = 1.725 \pm 0.005$.

GARTO, ARENDAL, NORWAY[64]

Pale olive green in section and sensibly isotropic; $n = 1.670 \pm 0.005$, varies somewhat. Much of this specimen is a brownish, vitreous alteration product. It is red brown in section and different grains vary greatly in optical properties. Part is isotropic, part is birefracting. The index of refraction varies greatly, but much is near 1.60±.

Larsen concludes from his microscopic study of the above five black and vitreous allanites that the so-called "allanite" is made up of a mixture of at least two minerals, one of which is birefracting, the other isotropic. The two types are distinct and their proportion in the same specimen is subject to great variation. Apparently the red, birefracting type is secondary, derived from the isotropic form, possibly without much, if any, change in chemical composition. Such relation between the two types might be the result either of alteration or of inversion, probably alteration.

The change from an anisotropic to an isotropic form, which may involve simply molecular rearrangement (paramorphism) or more or less chemical change, is regarded by some mineralogists as a form of alteration and is reported to have been observed in many minerals. Such change is claimed to be common for certain minerals like homilite, gadolinite, allanite, etcetera, in the "Brevik" region of Norway.

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[63] U. S. National Museum 84416.
[64] U. S. National Museum 49022.

Gadolinite, which is normally double refracting and crystalline, is, according to Dana,[65] more commonly completely isotropic both in the massive form and in crystals, and both forms may be observed in the same specimen in thin section. Dana attributes this change in optical structure to alteration from molecular rearrangement, for Petersson[66] has shown that both varieties have the same composition. The amorphous form of the mineral was made anisotropic and crystalline on heating, accompanied by other physical properties. Both forms are rendered brown by alteration—oxidation and hydration.

It is evident from the microscopic results detailed above that the composition of ordinary black vitreous allanite[66a] is open to doubt and should be investigated. Such study will involve a separation of the birefracting type from the isotropic form, and complete accurate analyses made of each and their optical and other properties determined. Microscopical and chemical studies of the two types will be continued with the hope of definitely determining whether the birefracting form is derived from the isotropic one by alteration or by inversion.

For the purposes of the present problem, however, investigation strongly points to sufficient variation in the composition of the so-called fresh allanite to at least influence and possibly to account for the heterogeneous character of the altered allanite product representing the same stage of weathering.

WEATHERED PRODUCT (CRUST) OF ALLANITE

MEGASCOPIC CHARACTERS

Studies made of allanite from Ellenville, New York; Chester County, Pennsylvania; Amherst, Fauquier, Nelson, and Roanoke counties, Virginia; Iredell, Madison, and Mitchell counties, North Carolina; Anderson County, South Carolina, and Baringer Hill, Llano County, Texas, show the formation of a reddish brown crust about the original mineral, which is clearly an alteration product derived from weathering. Many of the specimens are entirely encrusted by the alteration product, others are only partly encrusted, and others still exhibit only small patches here and there over the surface of the mineral.

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[65] E. S. Dana: A System of Mineralogy, 1900, pp. 506, 507, 510, 511, 512.

[66] G. Petersson: För. Förh., vol. 12, 1890, pp. 275-347; quoted by E. S. Dana.

[66a] In his studies of radio-active minerals found in Pennsylvania, Wherry has published a radiograph of allanite from East Bradford which is suggestive and may bear on the possible difference in composition of allanite. In the radiograph the outline of the allanite specimen is observed, but there are shown two small but pronounced white areas of very much greater intensity than other parts of the radiograph. Wherry designates the intensity of the mineral as "faintly active; barely discernible print in three weeks." (Edgar T. Wherry: Jour. Franklin Institute, vol. clxv, 1908, pl. iv, facing p. 66.)

In no case observed has the thickness of crust coating the larger masses of allanite exceeded a quarter of an inch and is usually less, while some of the grains and smaller masses may be entirely so altered. With only one exception (Anderson County, South Carolina), the weathered crust is sharply defined from the fresh appearing mineral, without gradation from one into the other. A typical specimen, however, from Anderson County, South Carolina, showed that weathering had developed in part along cleavage directions, and it was clearly observed to extend from the completely weathered crust into the fresh allanite along the cleavages.

The crust is usually friable and pulverulent, approaching at times an earthy character, but is often granular in appearance, exhibiting more or less of a waxy luster which becomes pronounced under the microscope. Its general appearance is that of a highly oxidized material which resembles more or less closely some forms of hydrated iron oxide. The analyses on page 485 confirm the high contents of ferric oxide and water in the composition of the weathered product.

As noted above, the prevailing color is reddish brown, but lighter shades of brownish yellow, grayish buff to nearly white, are observed. Masses of the mineral from several localities, especially emphasized in specimens from Amherst County, Virginia, sometimes exhibit a rudely zoned or layered crust, an inner reddish brown layer, and an outer lighter colored, very thin layer which may be almost white in some specimens from the Virginia locality. Separate analyses (I and IV of table on page 495) have been made of these two portions of the crust on specimens collected from Amherst County, Virginia.

Although the heterogeneous character of the fresh mineral from the different localities is indicated microscopically, there is no evidence for regarding the two unlike layers of the weathered crust as having been derived from a zonal arrangement of chemically different molecules in the fresh mineral. Indeed, the rudely layered structure of the weathered product is the result of alteration, and probably has its analogy in the lateritization of rocks as recently developed by Professor Lacroix,[67] who distinguishes in the laterites of French Guinea an inner zone of leaching (depárt) and an outer zone of concretion.

MICROSCOPIC CHARACTERS

Microscopic study of the weathered allanite crust from all the localities enumerated above (page 485), except Baringer Hill, Texas, and Fauquier

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[67] A. Lacroix: Nouvelles Archives du Musée, ser. V, tom. v, pp. 255-356.

County, Virginia, which were not studied microscopically, yielded similar results. For this reason the microscopic data obtained on the powder of the weathered product from the various localities in the Atlantic States are not tabulated separately, but are here summarized in order to avoid unnecessary repetition.

Microscopically the powdered crust is reddish brown in color, waxy in luster, and distinctly granular rather than earthy in character. It is heterogeneous in mineral composition, composed partly of birefracting grains and partly of isotropic ones, with probably the latter predominant. Both the birefracting and the isotropic grains are variable in physical properties and probably in composition.

Pleochroism, if developed, is extremely weak and not important; only noticeable in an occasional strongly colored grain. Index of refraction variable within wide limits, a number of grains ranging as low as 1.60 and a few above 1.85, with the average probably around 1.75. These figures apply both to the birefracting and to the isotropic grains. For the anisotropic grains the double refraction is very weak, but variable. Some grains exhibited entirely sharp and distinct extinction, and several indicated that they were probably optically positive (+). Occasional grains of quartz were identified in the powder of a number of specimens of the decayed product from different localities.

The evidence gained from both a microscopic and a chemical study of the powdered weathered product (crust) conclusively proves its heterogeneous character. Attempts to effect a separation of the birefracting grains from the isotropic ones for separate chemical analyses of each were unsuccessful. However, should a separation prove successful, chemical analyses of either the birefracting or isotropic grains would probably reveal inconstancy of composition in each, since the microscopic study reasonably establishes the heterogeneous character of both.

CHEMICAL COMPOSITION

For purposes of comparison analyses of the weathered product of allanite crust are brought together in the table below in the order of increasing silica:

Analyses of the weathered Product of Allanite from Virginia

	I	II	III	IV
SiO_2	8.05	8.48	18.66	21.37
TiO_2	.....	2.16	.....	.....
Al_2O_3	16.83	2.57	23.28	20.66
Ce_2O_3	7.13	6.44	1.30	21.90

	I	II	III	IV
Di_2O_3[68]	none	1.21	0.65	none
La_2O_3	none	trace	3.27	none
Fe_2O_3	37.14	47.31	34.48	12.24
FeO	none	trace	none	none
BeO	0.94	none	none	1.95
MgO	none	trace	0.29	none
CaO	none	2.45	none	none
Na_2O	none	none	0.43	none
K_2O	none	none	0.20	none
H_2O	29.55	29.24	17.16	21.37
	99.64	99.86	99.72	99.49

I. Inner red layer of weathered allanite crust from Amherst County, Virginia. J. R. Santos, analyst.

II. Weathered allanite crust from Roanoke County, Virginia. S. D. Gooch, analyst.

III. Weathered allanite crust from Nelson County, Virginia. E. P. Valentine, analyst.

IV. Outer white layer of weathered allanite crust from Amherst County, Virginia. J. R. Santos, analyst.

These analyses represent approximately a similar stage of advanced allanite weathering. They clearly show the composition of the allanite decayed product to be made up in each case of essentially the same constituents, but in widely varying percentage amounts. Without regard to their quantitative order, these are silica, alumina, ceria, ferric oxide, and water. Some didymia and lanthana are indicated in two of the analyses, and in one (III) lanthana exceeds ceria by 2½ times in amount—a reversal in the usual order of solubility of the salts of the two metals. Likewise the heterogeneous character of the weathered product has been shown from microscopic study composed of isotropic and of weakly birefracting types of variable physical properties and probably composition. Probably the bulk of the product is made up of the isotropic type, the general character of which, from the nature of many colloidal materials, argues for a single mineral in colloidal or metacolloidal form of variable composition rather than composed of a mixture of several minerals.

Some qualitative tests carried out by Prof. A. W. Giles at the request of the writer, on the reddish brown decayed product of allanite from four different localities, agree in most cases in showing the lack of homogeneity of the material. The tabulated results follow below. Similar tests made by Valentine on the decayed product from Nelson County, Virginia, gave the following results: Decomposed by HCl; heated on charcoal, the powder blackens and becomes magnetic; with borax bead reacts for iron; heated in closed tube, yields water having neutral reaction. Specific gravity in powder, 2.606.

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[68] Di is the symbol for old didymium, which is now known to be a mixture of neodymium, praseodymium, samarium, etcetera.

	Roanoke Co., Virginia	Amherst Co., Virginia	Anderson Co., South Carolina	Chester Co., Pennsylvania
Yields water in closed tube.	Faintly alkaline	Faintly alkaline	Neutral	Neutral
Soluble in hot dil. HCl.	Gelatinizes	Gelatinizes	Gelatinizes	Gelatinizes
Infusible BB. Residue insoluble or only slightly soluble.	Nonmagnetic	Nonmagnetic	Nonmagnetic	Magnetic
Presence of CO_2	Slight	Faint	None	None

WEATHERING OF ALLANITE IN VIRGINIA LOCALITIES

INTRODUCTORY STATEMENT

Fresh and weathered masses of allanite, weighing up to several pounds, from Amherst, Nelson, and Roanoke counties, Virginia, have afforded excellent material for a study of the weathering of the mineral and are regarded as typical for allanite alteration in general. Chemical analyses of both the fresh and the decomposed allanite from each locality have been made, which will serve to emphasize the difference in composition between the fresh and the weathered mineral. These are compared and the changes incident to weathering of the allanite are discussed below. Careful investigation of the mineral from the several localities, both in the field and in the laboratory, clearly shows the form of weathering to be chemical and not physical in nature.

PREVIOUS WORK

After a careful search of the literature, the writer has found records of only three analyses of the weathered product of allanite. These were made by Santos[69] and Valentine[70] on material collected from Amherst and Nelson counties, Virginia, and are quoted by both Dana[71] and Hintze.[72]

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[69] J. R. Santos: Chem. News, vol. 38, 1878, p. 95.

[70] E. P. Valentine: Am. Chem. Jour., vol. 7, 1885-1886, p. 178.

[71] E. S. Dana: A System of Mineralogy, 1900, 6th edition, p. 526.

[72] C. Hintze: Handbuch der Mineralogie, 1887, p. 276.

In 1878 analyses were made by Santos of the weathered product (crust) of allanite from Little Friar Mountain, Amherst County, Virginia, including a separate analysis each of (*a*) the outer white layer and (*b*) the inner red layer. Comparing these analyses of the weathered product with an analysis made of the fresh mineral from the same locality by Cabell[73] in 1874, Santos briefly called attention to the chemical changes incident to the weathering of the allanite. Later (1885) Valentine[74] analyzed the weathered crust of allanite occurring near Lowesville, Nelson County, Virginia, and in 1885 an analysis of the fresh mineral from the same locality was made by Memminger;[75] but a discussion of the chemical changes involved in the weathering of the mineral was not published.

ROANOKE COUNTY

Locality and mode of occurrence.—The allanite locality[76] in Roanoke County is a new one and is described here for the first time. The mineral occurs on that part of the Shepherd farm located on the crest of the Blue Ridge Mountains, in Roanoke County, within a few paces of the Franklin County line and in a direct line about 9 miles south of Roanoke City.

The allanite occurs as a constituent of a pegmatite body exposed by a small pit opened to a depth not exceeding 10 feet. Both the pegmatite dike and the inclosing rock are greatly weathered. Because of this fact it was not possible to measure the dip, strike, and width of the pegmatite. So far as could be determined by the opening made, the allanite is distributed irregularly through the pegmatite, but in quantity as grains and masses up to many pounds in weight, and to some extent in stringer-like bodies. A specimen of the massive, pitch-black allanite, intergrown with some quartz, and weighing nearly 3 pounds, contains a number of attached perfect crystals of allanite up to 15 mm. long by 5 mm. broad. Much of the surface of the massive specimen is highly oxidized and is encrusted with an appreciable thickness of the reddish-brown decomposition product.

The associated minerals are kaolin, derived from the decomposition of feldspar; dark-colored mica, more or less altered; quartz, dark yellow-green epidote, and some magnetite which exhibits good cleavage and in several specimens crystal faces. The magnetite contains on analysis approximately 1 per cent of TiO_2.

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[73] J. A. Cabell: Chem. News, vol. xxx, 1874, p. 141.

[74] E. P. Valentine: Loc. cit., p. 178.

[75] C. G. Memminger: Am. Chem. Jour., vol. 7, 1885-1886, p. 177.

[76] The writer visited the locality in company with S. D. Gooch during the summer of 1916, and unusually good specimens of the fresh and weathered allanite were secured and analyzed by Mr. Gooch in the chemical laboratory of the University of Virginia, with the results shown in the table on page 491.

The inclosing rock varies from even granular to porphyritic in texture and is the quartz-bearing variety of hypersthene syenite, the dominant rock type of the igneous complex forming the central core of the Blue Ridge Mountains in Virginia.[77] Farther down the northwest slope of the mountain, near the Shepherd home, excellent exposures of schist occur, followed by granite.

Fresh allanite.—The larger inner portion of each mass and fragment of the mineral collected seemed entirely fresh and showed the following physical properties: Color, black; streak, gray; cleavage, indistinct; fracture, uneven to subconchoidal; luster, vitreous; and hardness, about 6. Some surfaces are broken by tiny veinlets of a gray but unknown substance, which become more emphasized in the weathered crust of the mineral. With this exception, the fracture surfaces of the mineral appear very homogeneous. When examined under the microscope, the mineral is found to be composed of two forms, one of which is sensibly isotropic, the other birefracting and derived from the isotropic type by alteration or inversion, probably by alteration. The optical constants are given on page 481. An analysis of the fresh mineral is given in column I of the table below.

The allanite from the adjoining county on the northeast (Bedford), an analysis of which is given in column VIII of table on page 479, is grayish black and is appreciably lighter in color than the Roanoke County mineral. It weathers light yellow and buff to reddish brown. No analysis has been made of the weathered portion of the mineral from the Bedford County locality.

Weathered crust of allanite.—Every piece of the mineral, both large and small, taken from the opening on the Shepherd farm was coated with the decomposition product of allanite derived by weathering. This weathered crust ranged up to nearly a quarter of an inch in thickness in some of the larger pieces, and some of the smaller masses were entirely decomposed throughout without any trace of the original mineral. The color of the crust varied from yellowish brown to deep red brown, the latter being dominant, with frequently an outer exceedingly thin layer of a light gray to yellowish buff. The crust has a decidedly deeper red color in powdered form.

It is very fine-textured but porous, appears uniform in general appearance, and readily crumbles between the fingers to a powder which is usually free from grit. The two parts of the allanite, fresh mineral and decomposed crust, are sharply defined from each other, with no indication of gradual passage from one into the other. This is characteristic, with one exception, of all weathered portions of allanite that the writer has studied from many different localities.

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[77] Watson and Cline: Bull. Geol. Soc. Am., vol. 27, 1916, pp. 193-234.

Powder is soluble in hot dilute HCl yielding gelatinous silica; is infusible before the blow-pipe and non-magnetic; yields water on heating in closed tube, which reacts faintly alkaline; and reacts slightly for carbonates.

Microscopically the powdered crust was composed of a granular waxy material of deep red color, which was partly birefracting and partly isotropic, each type exhibiting variable physical properties and probably variable in chemical composition. Separation of the two types in sufficient quantity and purity for separate chemical analysis proved unsuccessful. After digesting a small portion of the powder for a few minutes in dilute HCl, the residue was washed and examined under the microscope. It was found to be of the same character as the undigested portion of powder described above, with no indication whatever of the presence of any undecomposed particles of allanite; but there appeared a sprinkling of minute, colorless, and double refracting, crystalline grains, which were referred to quartz. A portion of the powdered crust yielded Prof. F. P. Dunnington 11.03 per cent total silica, 7.78 per cent of which was soluble in a 5 per cent solution of sodium carbonate, leaving 3.25 per cent insoluble and reckoned as crystalline silica.

Chemical analyses and their discussion.—In columns I and II are given the analyses of the fresh and weathered mineral, and in columns III, IV, and V the loss and gain of the various constituents calculated on a ferric oxide constant basis.[78]

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[78] *Method employed in calculations.*—In order to trace the changes that have taken place in the weathering of siliceous crystalline rocks, recent investigators (G. P. Merrill: A Treatise on Rocks, Rock-weathering, and Soils. The Macmillan Co., N. Y., 1906, 400 pages; see especially pp. 187-188) have assumed one of the essential constituents to remain constant as a basis for comparing analyses of the fresh and weathered rock. Investigations have shown that of the essential constituents in siliceous crystalline rocks alumina and iron oxide are the most refractory and have suffered least from leaching and removal in solution. For all cases thus far studied either alumina or iron oxide has been assumed as the constant factor for calculating the percentage loss and gain of each constituent as compared with that in the original rock.

This method is employed by the writer in the present paper for comparing analyses of fresh and weathered allanite in the attempt to trace the changes in the decomposition of the mineral. While this method has not been applied to the weathering of minerals, so far as the writer is aware, there appears to be no valid reason why it is not as applicable to the weathering of certain minerals as to rocks. In each of the cases described in this paper ferric oxide appears to have suffered the least amount of loss during the weathering of the mineral and has been taken as the constant factor for comparison.

Analyses of fresh and decomposed Allanite from Roanoke County, Virginia

(S. D. Gooch, analyst)

	I	II	III	IV	V
SiO_2	31.71	8.48	6.77	93.23	29.56
TiO_2	.86	2.16	63.52	36.48	.31
Al_2O_3	9.32	2.57	6.98	93.02	8.67
Ce_2O_3	13.90	6.44	11.72	88.28	12.27
Di_2O_3	9.07	1.21	3.34	96.66	8.77
La_2O_3	1.25	trace	0.00	100.00	1.25
Fe_2O_3	11.95	47.31	100.00	0.00	0.00
FeO	8.95	trace	0.00	0.00	0.00
MnO	.18	trace	0.00	100.00	0.18
CaO	11.02	2.45	5.62	94.38	10.40
MgO	.96	trace	0.00	100.00	0.96
Na_2O K_2O	.16	none	0.00	100.00	0.16
H_2O	.86	29.24	100.00	0.00	0.00
	100.19	99.86	......	......	72.53

I. Analysis of fresh allanite.
II. Analysis of decomposed allanite.
III. Calculated percentage of each constituent saved.
IV. Calculated percentage of each constituent lost.
V. Calculated percentage loss for the entire mineral.

The figures indicate that the decomposition of the mineral has been accomplished by hydration, oxidation, carbonation, and solution—the important chemical reactions in the belt of weathering.

The increase or gain in water (hydration) is large. Ferrous oxide has been oxidized to ferric oxide, and it is believed that most, if not all, of it has been retained, although it is not improbable that some has been lost through solution.

Absence of carbonates is indicated in the analysis, but a careful test made on a separate portion of the weathered product indicated the slight presence of carbonates. Nevertheless carbonation is regarded as one of

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The formula given by Doctor Merrill for rocks is employed here for allanite. It is as follows:

$$\frac{A}{B \times C} = x\text{; and } 100 - x = y,$$

in which A = the percentage in any constituent in the residual material; B = the percentage of the same constituent in the fresh rock, and C = the quotient obtained by dividing the percentage amount of alumina or iron oxide (iron oxide in this paper) of the residual material by that in the fresh rock, the final quotient being multiplied by 100. x then equals the percentage of the original constituent saved in the residue, and y the percentage of the same constituent lost.

the important chemical reactions in the decomposition of the mineral, for in the weathering of lime and magnesia-bearing rocks these constituents invariably suffer loss from leaching in the form of soluble carbonates (bicarbonates). The percentage loss of lime and magnesia certainly, and of the cerium earths probably, indicated in the table above, is due to the formation of soluble carbonates and their removal in solution.

Simultaneously with the production of carbonates, most of the silica separated as colloidal silicic acid, which is readily soluble, and was removed in solution,[79] which accounts for the unusually large percentage loss in this constituent. Alumina has likewise been removed in larger quantity than usual in weathering, although several cases have been recorded among siliceous crystalline rocks in which the loss in this constituent equals that in the case here described.

Special attention is directed to the large percentage loss of the cerium earths, the figures indicating that all of the lanthana, 96.66 per cent of the didymia, and 88.28 per cent of the ceria have been removed by solution. These figures should be compared with those for the Amherst and Nelson counties localities.

The decomposition of the mineral has been accompanied by a total loss from leaching of 72.53 per cent, or nearly three-fourths of the original material. Of the original silica, 93.23 per cent has been lost, 93.02 per cent of alumina, and 36.48 per cent of the titania, while all of the iron oxide has been retained. All of the magnesia and alkalies and 94.38 per cent of the lime have disappeared.

NELSON COUNTY

Locality and mode of occurrence.—The allanite of Nelson County is found about 3 miles east of Lowesville. It has been described by C. G. Memminger,[80] who analyzed it with the results shown in column I of the table below. The allanite is reported to occur in a vein at a depth of 4 or 5 feet below the surface in the form of detached masses imbedded in a "clay" derived from its weathering. The masses of mineral were of rounded outline and covered with a thin yellowish white crust formed by its weathering.

Fresh allanite.—The general properties of the allanite from the Nelson County locality are as follows: Color, pitch black; luster, resinous; fracture, uneven, with traces of cleavage; streak, greenish gray; hardness, 6; and specific gravity, 3.59. It fuses before the blow-pipe with intumescence and is easily decomposed by HCl with the separation of gelatinous silica.

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[79] L. Kahlenberg and A. T. Lincoln: Jour. Phys. Chem., vol. 2, 1898, pp. 77-90.
C. R. Van Hise: Monograph xlii, U. S. Geol. Survey, 1904.

[80] C. G. Memminger: Am. Chem. Jour., vol. vii, 1885-1886, p. 177.

Weathered allanite.—The weathered product of the fresh allanite (I) analyzed by E. P. Valentine[81] (II of table below) was described by him as compact earthy, breaking in angular pieces of brownish yellow, yellowish red to red in color, but crumbling readily between the fingers and not plastic. When heated in a closed tube, it yielded water which reacted neutral, and blackened when heated on charcoal and became magnetic. It was decomposed by HCl and was decomposed and partially dissolved on boiling with NaOH. Particles of the crushed material were examined microscopically and found to be transparent, and of a wine-yellow color, but without birefringence.

Chemical analyses and their discussion.—The special features to which attention is called in the analyses are (1) the large increase or gain in water (hydration), which is considerably less than for the mineral from either Amherst or Roanoke County; (2) the complete oxidation of ferrous to ferric oxide, and (3) the large total loss of the original mineral removed in solution, amounting to 74.63 per cent.

Analyses of fresh and decomposed Allanite from Nelson County, Virginia

	I[82]	II	III	IV	V
SiO_2	30.04	18.66	9.12	90.88	27.30
Al_2O_3	16.10	23.28	21.23	78.77	12.68
Ce_2O_3	11.61	1.30	1.64	98.36	11.42
Di_2O_3	5.39	.65	1.77	98.23	5.29
La_2O_3	4.11	3.27	11.68	88.32	3.63
Fe_2O_3	5.06	34.48	100.00	0.00	0.00
FeO	9.89	none	0.00	100.00	13.02
CaO	13.02	none			
MgO	1.11	.29	3.84	96.16	1.07
Na_2O	.28	.43	22.63	77.37	.22
K_2O	.02	.20	100.00	0.00	0.00
H_2O	2.56	17.16	100.00	0.00	0.00
	99.36	99.72	......	......	74.63
Sp. gr.	3.59	2.606			

I. Analysis of fresh allanite. C. G. Memminger, analyst.
II. Analysis of weathered allanite. E. P. Valentine, analyst.
III. Calculated percentage of each constituent saved.
IV. Calculated percentage of each constituent lost.
V. Calculated percentage loss for the entire mineral.

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[81] E. P. Valentine: Am. Chem. Jour., vol. vii, 1885-1886, p. 178.

[82] Includes SnO_2, 0.17 per cent; MnO, trace.

According to the analyses and calculations tabulated above, the decomposition of the mineral has been accompanied by a total loss from leaching of 74.63 per cent, or three-fourths of the original material. This includes the unusually large percentage loss of each of the principal constituents in the proportions given in column IV, amounting in every case to more than three-fourths of the original ones. All of the lime has disappeared and with it most of the magnesia, the earths of the cerium group, silica, and much of the alumina. The alkalies are present in such small quantity in the fresh mineral as to render conclusions concerning them of doubtful value.

AMHERST COUNTY

Locality and mode of occurrence.—The occurrence of allanite on the northwest slope of Friar Mountain, in Amherst County, Virginia, 15 miles north of Amherst Courthouse, is one of the most notable in this country, since the mineral is found in unusual quantity. The allanite occurs in pegmatite mostly as detached lumps and masses up to 4 or 5 pounds in weight. In addition to feldspar and quartz, the associated minerals are magnetite and sparingly the rare mineral sipylite, a niobate of erbium chiefly, with the metals of the cerium group, etcetera. The feldspar is more or less kaolinized from weathering.

Fresh allanite.—The fresh allanite from this locality very closely resembles that from Roanoke County described on pages 488 to 492. It is black in color, has vitreous luster, and shows traces of cleavage; fracture, uneven; streak, gray; hardness, nearly 6; and specific gravity, 3.83. All of the mineral examined microscopically from the Amherst County locality was birefracting, the optical properties of which were determined and are given on page 481.

Weathered allanite.—Lumps and masses of the mineral are usually coated with a crust, which has resulted from weathering, varying from a mere film to, in extreme cases, more than a quarter of an inch in thickness. Much of the crust is dark reddish brown to brick red in color, sometimes light yellowish to buff, rarely nearly white. In some cases the crust exhibits a rudely concentric structure and is separable into two parts, an outer exceedingly thin layer of nearly white color and an inner one of brick red color, both being pulverulent and more or less earthy in character. This layered structure is not original in the fresh mineral, but is plainly the result of alteration from weathering.

Separate analyses of the two parts of the crust are given in the table below. The brick red crust dissolves in hot HCl, with the separation of gelatinous silica; is infusible before the blow-pipe, the residue being nonmagnetic; yields water when heated in closed tube, which reacts faintly alkaline; and reacts faintly for carbonates. Several tests with hot acid were made on the lighter colored crust, which resulted in yielding little or no gelatinous silica, but an insoluble residue remained composed chiefly of silica. A portion of the powdered red crust yielded Prof. F. P. Dunnington 15.40 per cent total SiO_2, 12.50 per cent of which was insoluble in a 5 per cent solution of sodium carbonate, the difference, 2.9 per cent, being accounted amorphous silica. Similar determinations made of total soluble and insoluble SiO_2 on the weathered crust from Roanoke County showed nearly 75 per cent of the total SiO_2 to be soluble in a 5 per cent soda solution (see pages 491-492).

Microscopic examination of several separate portions of the powdered crust showed it to be identical with that from other localities. It was composed partly of isotropic and partly of weak birefracting grains, each type exhibiting considerable variation in physical properties. The light colored powder contained a goodly sprinkle of minute colorless grains that were double refracting and were identified as probably quartz.

Chemical analyses and their discussion.—In the subjoined table are given analyses of the fresh allanite in column I, and of the inner red layer of weathered allanite in column II, and of the outer white layer in column VI. Columns III, IV, and V give the gain and loss in constituents by comparing the analyses of the fresh and the weathered inner red layer of the mineral on a ferric oxide constant basis. Likewise figures showing gain and loss in constituents of the outer white layer when compared with the fresh mineral on the same basis are given in columns VII, VIII, and IX.

Analyses of fresh and decomposed Allanite from Amherst County, Virginia

		Weathered allanite, inner red layer				Weathered allanite, outer white layer			
	I	II	III	IV	V	VI	VII	VIII	IX
SiO_2	31.23	8.05	2.42	97.58	30.47	21.37	19.55	80.45	25.12
Al_2O_3	16.45	16.83	9.61	90.39	14.87	20.66	35.88	64.12	10.55
Ce_2O_3	11.24	7.13	5.98	94.02	10.57	21.90	55.67	44.33	4.98
Di_2O_3 La_2O_3	9.90	none	0.00	100.00	9.90	none	0.00	100.00	9.90
Y_2O_3	1.65	none	0.00	100.00	1.65	none	0.00	100.00	1.65
Fe_2O_3	3.49	37.14	100.00	0.00	0.00	12.24	100.00	0.00	0.00
FeO	13.67	none	36.86	0.00	0.00	none	0.00	0.00	0.00
BeO	0.24	.94		63.14	.15	1.95	23.21	76.79	.18
CaO	8.69	none	0.00	100.00	8.69	none	0.00	100.00	8.69
MgO	.22	none	0.00	100.00	0.22	none	0.00	100.00	0.22
H_2O	2.28	29.55	100.00	0.00	0.00	21.37	100.00	0.00	0.00
	99.06	99.64			76.52	99.49			61.29

I. Analysis of fresh allanite. J. A. Cabell, analyst.
II. Analysis of weathered allanite—inner red layer (crust). J. R. Santos, analyst.
III. Calculated percentage of each constituent saved.
IV. Calculated percentage of each constituent lost.
V. Calculated percentage loss for the entire mineral.
VI. Analysis of weathered allanite—outer white layer (crust). J. R. Santos, analyst.
VII. Calculated percentage of each constituent saved.
VIII. Calculated percentage of each constituent lost.
IX. Calculated percentage loss for the entire mineral.

The figures disclose some interesting differences, which are difficult of explanation, for the two parts of the weathered crust. Thus, when the analyses of the two weathered portions of the mineral are compared, it will be observed that the inner red layer contains less SiO_2, Al_2O_3, Ce_2O_3, and BeO, and more Fe_2O_3 and H_2O, than the outer white layer, while both agree in the absence of Di_2O_3, La_2O_3, Y_2O_3, FeO, CaO, and MgO. These differences are brought out in a striking manner in the figures given in columns IV and VIII, which represent the percentage loss of each constituent calculated on a ferric oxide basis. When compared in the usual way with the analysis of the fresh mineral, we find that the inner layer has suffered a loss from leaching of 76.52 per cent of the original mineral as against a loss of only 61.29 per cent for the outer layer, just the reverse of what would normally be expected. Each constituent of the inner red layer has been removed in larger amount than that of the outer white layer, as indicated in the comparison of figures in column IV (inner red layer) with those in column VIII (outer white layer) of table on page 495. More puzzling still is the fact that the outer layer contains more than 12 per cent of ferric oxide and is white in color. It is suggested that, of the several possible explanations considered, probably the most likely one to account for this anomalous condition is the existence of the iron in combination with the other constituents in some new colloidal or metacolloidal form, whose properties are yet unknown. Further investigation is needed to clear up this point.

Discussion of Results

The reddish brown weathered product of allanite from the many localities studied has been shown, both chemically and microscopically, to be variable in composition and not susceptible of definite chemical expression. As indicated by the analyses, essentially the same constituents enter into its composition, but in greatly varying ratios. In the most advanced stage of weathering the weathered product is composed of a few constituents, chiefly silica, alumina, ferric oxide, ceria,[83] and water, all the other constituents of the fresh mineral having been nearly or completely removed in soluble form by leaching. When compared with analyses of the corresponding fresh mineral from which the weathered product has been derived, each constituent on a ferric oxide constant basis has suffered loss from leaching, the more soluble ones having entirely disappeared and the more refractory ones having been removed in unusually large amount.

In common with the weathering of rocks and minerals in general, the change in allanite has been accompanied by a large increase in water (hydration), there being present in the decomposed product nearly 30 per cent of water. Allanite which appears fresh, but on analysis contains several per cent of water, is regarded as an altered form of the mineral, which often contains some CO_2, and slight oxidation is sometimes indicated.

The most patent reaction involved in the alteration, and one which accompanied hydration, was oxidation, whereby ferrous oxide was changed to ferric oxide. For the cases studied ferric oxide was retained in largest amount, and has been assumed as the constant factor for calculating the percentage amounts lost and saved of the other constituents. It seems clear in one case at least that this constituent has suffered some loss from leaching; but the process of oxidation must have taken place, as a rule, in a sufficient supply of free oxygen to convert the iron into the insoluble ferric form.

One of the most important as well as interesting facts developed in this study is the large but unequal percentage amounts of the rare earths lost by leaching. With only one exception (Nelson County, Virginia), cerium has proved to be the most refractory of the rare earths, and although lost in large amounts it has been partly retained in every case, and is an important constituent of the weathered product. In several cases the analyses indicate that other rare earths present in the fresh mineral have suffered complete loss. Spectroscopic examination by Santos of the outer white layer of the weathered allanite crust from Amherst County, Virginia, failed to show the absorption bands of didymium, so complete was its removal.

The soluble form in which the cerium earths have been leached from allanite on weathering is important, but is probably less conclusive than for other constituents, since their chemistry is not so well known. It is known that the neutral and basic carbonates of the cerium metals are insoluble in water, while the double carbonates are sparingly soluble and are decomposed by water. Cerous and ceric carbonates are reported to be insoluble in cold water and carbon dioxide, while lanthanum carbonate is insoluble in cold water, but is slightly soluble in carbonated water. All carbonates of the cerium metals are soluble in dilute acids.

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[83] The decayed product of allanite from Nelson County, Virginia, contains lanthana in amount about 2½ times greater than ceria.

These are results obtained in the laboratory, where the time factor is very brief and the concentrations greater than in nature, and are not comparable with the natural conditions in the belt of weathering where the mineral allanite in common with all others may be exposed for an indefinite period of time to a constant supply of weak solutions. Again, the rare earth elements, considered as trivalent at present, are known to bear a general chemical resemblance to those of the alkaline earths, which under conditions of weathering are always removed as soluble carbonates.

From our knowledge therefore of the chemistry of the cerium group of metals, it seems reasonable to regard their loss on weathering as due to the formation of soluble carbonates removed in solution. That such carbonates are formed from the alteration of allanite has been stated by Clarke,[84] who says: "Allanite is often much altered, yielding carbonates of the cerium group, together with earthy products of uncertain character."

Although tests were made for the presence of carbonates on portions of the weathered crust of the mineral from different localities with positive results in only two cases, carbonation is regarded as one of the important reactions in the alteration, and the cerium earths are believed to have been removed in the form of soluble carbonates, as were certainly the lime and magnesia. Of the rare earths present in allanite, cerium is the least soluble and is partly retained in every case, entering as an important constituent into the composition of the weathered product.

Lanthanite, a hydrous lanthanum carbonate, is reported from a few localities and is the only known native carbonate of the cerium group of metals. It has been reported in scales and scaly incrustations on allanite from Essex County, New York,[85] and Baringer Hill, Llano County, Texas,[86] and is undoubtedly a secondary mineral derived by alteration from allanite.

The variable but unusually large percentage losses of the remaining essential constituents, silica and alumina, have their analogy in rock decay, many examples of which are on record[87] and need not be discussed here.

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[84] F. W. Clarke: The data of geochemistry. Bull. 616, U. S. Geol. Survey, 1916, p. 408.

[85] E. S. Dana: A System of Mineralogy, 1900, p. 302.

[86] F. L. Hess: Bull. 340, U. S. Geol. Survey, 1908, p. 292.

CONCLUSIONS

The following conclusions seem warranted from this investigation:

1. Allanite has wide distribution as a primary minor accessory mineral in many kinds of igneous rocks.

2. Of the several modes of occurrence, the most important as regards size and quantity of mineral is in pegmatite bodies.

3. The ordinary black vitreous allanite is apparently not homogeneous in composition, but is made up of at least two types, the proportions of which are subject to wide variation in different specimens examined. One is isotropic; the other is birefracting and derived from the former by either alteration with or without appreciable change in chemical composition or by inversion, but probably by alteration.

4. When found at or near the surface, the allanite masses are usually partially or entirely encrusted with a reddish brown alteration product, sometimes of lighter color, closely resembling in general appearance some form of hydrous iron oxide, which is clearly the result of weathering (decomposition).

5. The weathered product of allanite is not homogeneous except in the sense of many colloidal materials, but is definitely shown microscopically to be heterogeneous in character, composed of a variant mixture of isotropic and weakly birefracting grains, each type of which varies considerably in physical properties and probably in chemical composition. The bulk of the decomposition product, however, is apparently composed of an isotropic substance in colloidal or metacolloidal form of variable composition.

6. Chemical analyses of the weathered product likewise disclose its variable nature, and when compared with analyses of the supposed fresh mineral the processes involved in the change are chemical, the principal reactions being hydration, oxidation, carbonation, and solution, or those common to the belt of weathering. For the stage of decay represented the transformation from fresh to decomposed mineral has been accompanied by a total loss from leaching of approximately 75 per cent of the original material, as calculated on a ferric oxide constant basis.

7. When chemical analyses of the decayed product are compared, the difference in composition is found to be one not of unlike constituents,

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[87] G. P. Merrill: Rocks, Rock-weathering, and Soils. The Macmillan Co., N. Y., 1906, 400 pages.

but of essentially the same constituents in widely varying ratios, which finds expression in inequality of leaching. The weathered product is composed essentially of water, ferric oxide, alumina, ceria, and silica, the other constituents of the fresh mineral having been removed, with but few exceptions almost, if not entirely, in solution. It does not represent a homogeneous substance of definite chemical composition and can not be expressed by any fixed chemical formula.

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TECTONIC LINES IN THE HAWAIIAN ISLANDS[1]

BY SIDNEY POWERS

(Presented before the Society December 30, 1915)

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INTRODUCTION

During the past eighty years the Hawaiian Islands have been visited by various geologists, few of whom saw all the islands of the group or remained on the islands for any considerable length of time. Certain of the tectonic features of the islands have received only scant attention, while others have never been examined. It is the purpose of this paper to call attention to those features which have not been described as well as to offer suggestions concerning those previously noted. Various theories which have been proposed to account for the alignment of the volcanoes, both active and extinct, and for their age relations, are reviewed in the light of a recent reconnaissance on every island of the group.

SPACING OF VOLCANOES

A notable alignment and spacing of the volcanoes in the island groups of the Pacific was noted at an early date by Dana in the Hawaiian Islands and by Darwin in the Galapagos. Many similar lines have since been noted, as in Java, and many suggestions have been made concerning the origin and significance of the phenomena.

On the Hawaiian Islands the long extinct volcano which built the island of Kauai on one end of the inhabited chain of islands and the active Mauna Loa and Kilauea on the other end led Dana to point out that the volcanoes had arisen along a rent in the floor of the Pacific Ocean, and to suggest that the order of activity had been: Kauai, western Oahu, western Maui, eastern Oahu, northwestern Hawaii, southwestern Maui, and

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[1] Manuscript received by the Secretary of the Society October 3, 1916.

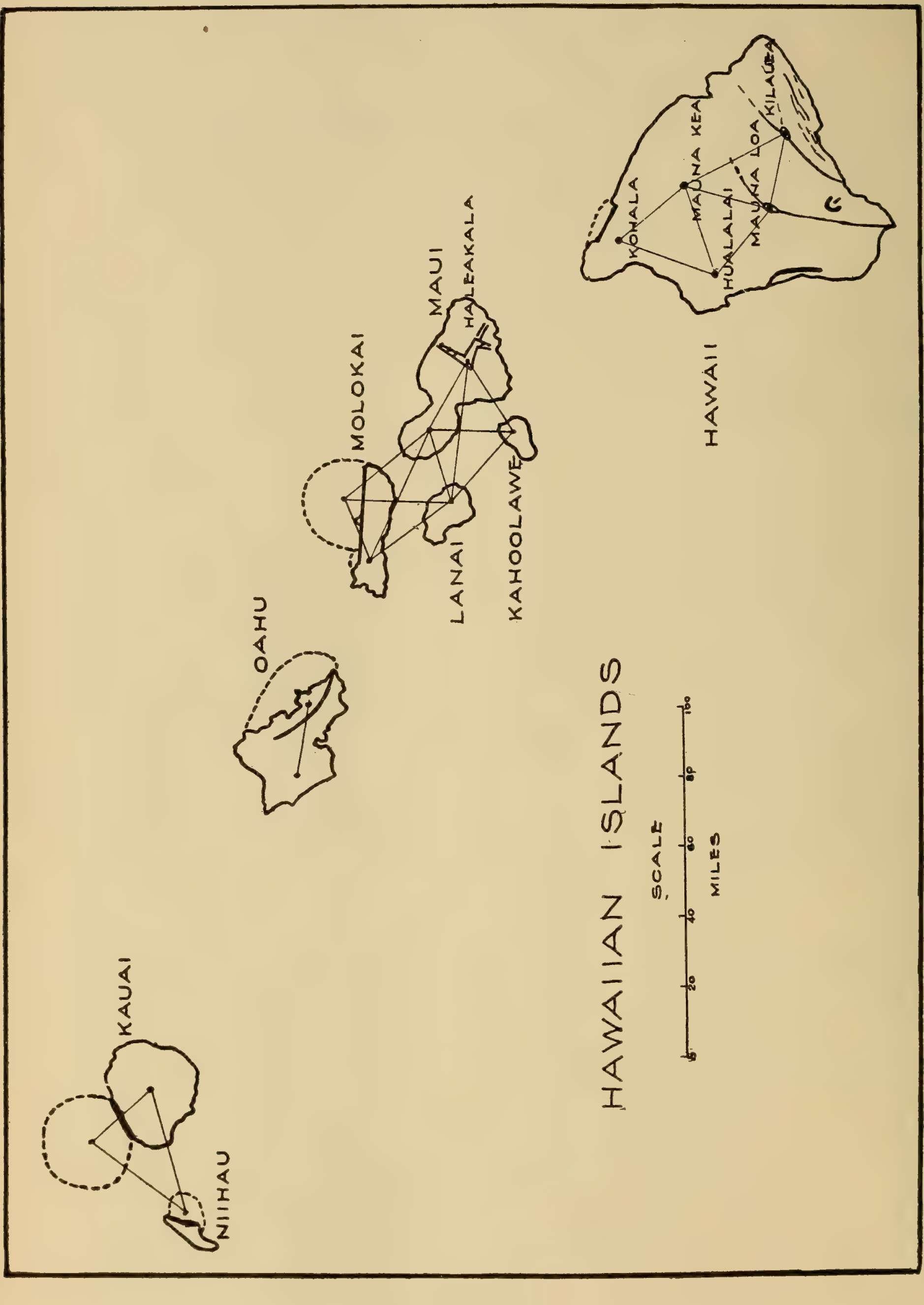
KAUAI
NIIHAU
OAHU
MOLOKAI
MAUI
HALEAKALA
LANAI
KAHOOLAWE
HAWAII
KOHALA
MAUNA KEA
HUALALAI
MAUNA LOA
KILAUEA
HAWAIIAN ISLANDS
SCALE
0
20
40
60
80
100
MILES

FIGURE 1.—*Map of the Hawaiian Islands*

Showing the centers of activity (dots joined by fine lines), the original outlines of the volcanoes (dashes), and the principal rift and fault lines connected with the breakdown of the volcanoes (heavy lines)

Mauna Loa.[2] Hawaii, while not the most recent island, remained active after the others. Kilauea was considered to have originated in the opening of a fissure to give exit to the lavas of Mauna Loa, but Dana admitted the possibility of overflows having taken place from Kilauea.

The relative age and the origin of Kilauea and Mauna Loa as suggested by Dana was not accepted by Brigham, Dutton, or Green, and later Dana himself reached a different conclusion. Brigham and Green suggested a separate origin for these two volcanoes, but Green proposed an entirely new hypothesis for the arrangement of the volcanic centers—that the volcanoes had arisen at regular distances on three sets of parallel lines, making angles of 60° with each other and spaced 20 miles apart.[3] This was the first time that attention was called to the uniform spacing of the volcanoes on the Hawaiian Islands and to the location of the vents at the intersection of fissures as Darwin had noted in the Galapagos. Dutton, before Green, had suggested that Kilauea and Mauna Loa were distinct volcanoes which had grown together,[4] and that each had originated at the intersection of two entirely different fissure lines.

After a second visit to the Hawaiian Islands in 1887, Dana stated that the volcanic centers of the group represented "two parallel ranges of islands,"[5] called the Kea Range on the north and the Loa Range on the south. Kilauea, according to this scheme, fell into the Kea Range and was, for this and other reasons, considered to be independent of Mauna Loa and to probably be younger than either Mauna Loa or Mauna Kea.

Further suggestions regarding the alignment of the vents were made by Alexander and by Woodworth. The former suggested that of the two intersecting fissures at which each vent were formed, one was in the course of the trend of the islands and the other was transverse to this trend.[6] Woodworth compared the arrangement to that of a major fracture system and said:

> "A double line of volcanoes like the Hawaiian does not necessarily imply that there must exist two great parallel fissures in the earth's crust. A single great torsion crack with the attendant fringe of border fractures in the superficial layer of the crust, or simple fracturing in accordance with this structure will account for all the phenomena of distribution of volcanoes in couplets along the double line. The commonly accepted view of two parallel fissures fails to account for the occurrence of the volcanoes in couplets and for the interval between them."[7]

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[2] U. S. Exploring Expedition, 1838-1842, Geology, pp. 282, 414-416.

[3] W. L. Green: Vestiges of a molten globe, vol. 2, Honolulu, 1887.

[4] Hawaiian volcanoes, U. S. Geol. Survey, 4th Ann. Rept., 1882-1883, p. 120; Am. Jour. Sci., vol. 25, 1883, pp. 221-226.

[5] Characteristics of volcanoes, New York, 1891, p. 262.

[6] J. M. Alexander: Am. Jour. Sci., vol. 37, 1888, p. 38.

[7] J. B. Woodworth: On the fracture system of joints, with remarks on certain great fractures. Proc. Boston Soc. Nat. Hist., vol. 27, 1896, p. 182.

More recent views on the relationship of Kilauea and Mauna Loa have been advanced by Hitchcock, H. B. Guppy, Daly, and Jaggar. Hitchcock[8] decided that these volcanoes were distinct above sealevel, but perhaps connected at a greater depth. Guppy[9] concluded from a study of spring waters that Mauna Loa and Kilauea are separate centers of influence.

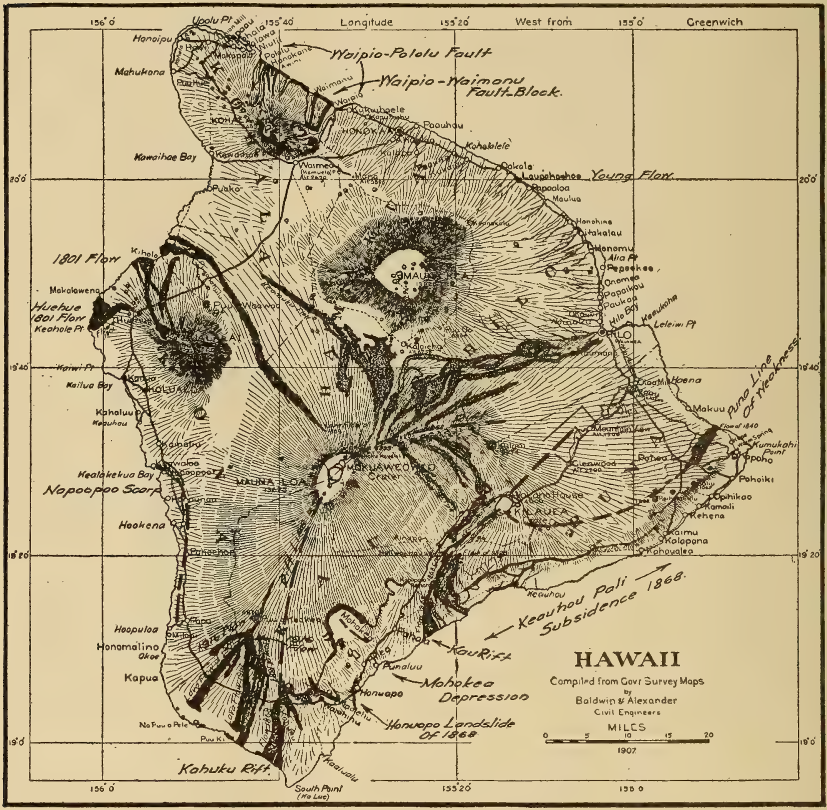
156° 0'
155° 40'
Longitude
155° 20'
West from
155° 0'
Greenwich
20° 0'
19° 40'
19° 20'
19° 0'
Upolu Pt
Honoipu
Mahukona
Niulii
Pololu
Honokane
Waipio-Pololu Fault
Waimanu
Waipio
Waipio-Waimanu Fault-Block.
Kukuihaele
KOHALA
HONOKAA
Paauhau
Kawaihae Bay
Kawaihae
Waimea
Kaholalele
Ookala
Laupahoehoe
Young Flow.
Papaaloa
Maulua
Puako
Honohina
Hakalau
Honomu
Alia Pt
Pepeekee
Onomea
Papaikou
Paukaa
Hilo Bay
Keaukaha
Leleiwi Pt
HILO
Kiholo
1801 Flow
Makalawena
Huehue 1801 Flow
Keahole Pt
Puu Waawaa
MAUNA KEA
Kalaieha
Kaumana
Kaiwi Pt
Kailua Bay
HUALALAI
Kahaluu
Keauhou
Olaa Mill
Haena
Makuu
Puna Line Of Weakness.
Flow of 1840
Warm Spring
Kumukahi Point
Pohoiki
Opihikao
Kamaili
Kehena
Kaimu
Kalapana
Kahaualea
Mountain View
Glenwood
Volcano House
KILAUEA
Kealakekua Bay
Napoopoo Scarp
Hookena
MOKUAWEOWEO Crater
MAUNA LOA
Hoopuloa
Honomalino
Okoe
Kapua
Na Puu a Pele
Puu Ki
Kohuku Rift.
South Point (Ka Lae)
Kaalualu
Waiohinu
Honuapo
Punaluu
Pahala
Mohokea
Kau Rift
Mohokea Depression
Honuapo Landslide Of 1868
Keauhou
Keauhou Pali Subsidence 1868.
HAWAII
Compiled from Govt Survey Maps
by
Baldwin & Alexander
Civil Engineers
MILES
0
5
10
15
20
1907

FIGURE 2.—*Map of Hawaii*

Showing Kahuku, Kau, Puna, and two unnamed rift lines; Napcopoo, Kaiohinu, Mohokea, Keauhou, Waipio-Waimanu, and Waipio-Pololu fault-lines. The 1916 flow started from above Puu o Keokeo instead of below this group of cones, as here shown.

A satellitic origin of Kilauea on the flanks of Mauna Loa as a laccolith which has given rise to the elevation at Kilauea and to the probable decrease in activity of that volcano has been elaborated by Prof. R. A. Daly.[10] This theory is supported by the fact that Kilauea is separated from Mauna Loa by a low depression.

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[8] Hawaii and its volcanoes, Honolulu, 1911, p. 261.

[9] Cited by Hitchcock, loc. cit., pp. 131-132.

[10] The nature of volcanic action. Proc. Am. Acad. Arts and Sci., vol. 47, 1911, pp. 109-116.

Quite the opposite view concerning the relative age of these two active volcanoes is taken by Jaggar, who, in a recent paper[11] on the problem, has called attention to the rhythmic arrangement of Kilauea, Mauna Loa, and Hualalai around Mauna Kea as a center. Along the Hawaiian rift the lava is supposed to have migrated from Kohala to Mauna Kea, later to Hualalai as Mauna Kea became extinct, then to Kilauea, and finally to Mauna Loa as Kilauea became decadent.

Better maps of the Hawaiian Islands and a closer examination of the original centers of activity may aid in elucidating the problem of the arrangement of the vents and of their relative age. It must be noted that the original central vents were not all located in the portions of the islands now remaining. Kauai was originally a volcanic doublet, the western half of which has disappeared. Niihau is but a remnant of the original volcano, the center of which was east of the present island. The Waianae volcano of western Oahu was centered not far northwest of the Kolekole Pass, if we are to judge from the great number of dikes in that vicinity and from the dip of the flows; and the Koolau volcano of eastern Oahu may have risen from a point between the Pali and Kaneohe, judging from the same reasons. The Wailau volcano of eastern Molokai rose from a point north of the present island.

Measurements of distances between centers of activity are as follows:

		Miles
Kauai:	Waialeale to northwestern center	21
	Waialeale to Niihau center	33
	Northwestern center to Niihau center	35
Oahu:	Waianae—Koolau center	22½
Molokai:	Mauna Loa—Wailau center	22½
	Mauna Loa—Lanai center	28
	Wailau—West Maui center	28½
	Wailau—Lanai center	28
Maui:	West Maui—Haleakala	25
	West Maui—Lanai	19½
	West Maui—Kahoolawe	23
	Kahoolawe—Lanai	26
	Kahoolawe—Haleakala	25
Hawaii:	Kohala—Mauna Kea	23
	Kohala—Hualalai	28½
	Mauna Kea—Hualalai	27½
	Mauna Kea—Kilauea	31
	Mauna Kea—Mauna Loa	25
	Mauna Loa—Hualalai	24
	Mauna Loa—Kilauea	21

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[11] T. A. Jaggar, Jr.: The cross of Hawaii, Honolulu, 1912, 12 pp.

The average distance between these vents is 25.6 miles, the maximum about 35 miles and the minimum about 19 miles. The Waialeale center of Kauai is 100 miles from the Waianae center of western Oahu, the Koolau center of eastern Oahu is 44 miles from Mauna Loa (western Molokai), and the Kohala center is 52 miles from Haleakala. Dividing these distances into four, two, and two units respectively, the average unit is 24.5 miles, as if the spaces between the islands had the same significance as the spaces between the centers of activity now visible above sealevel.

It was the regular arrangement above tabulated which led W. L. Green to his hypothesis of the triangular network of lines with the centers of activity at the intersections of these lines; and, while the actual arrangement does not fit Green's scheme, there appears to be an underlying cause for the arrangement. Two parallel lines can be drawn along the axis of the islands which will fall near the centers of activity, and these lines may be intersected by a set of lines transverse to their axis which will fall on these centers and which, by curving, may be made to fall along the rift lines visible on the flanks of Mauna Loa and Kilauea.

A theory explaining the origin of the volcanoes along intersecting curved lines is supported by the field evidence of a row of cones on the flank of Kohala pointing toward Haleakala and of a row of cones on Haleakala pointing toward Kahoolawe and almost connecting these two volcanoes above sealevel. On the contrary, the lines of weakness now seen may have no connection with those beneath the volcanic piles. The breakdown of the volcanoes has no connection with either the island alignment or with any hypothetical cross-lines.

The most satisfactory theory yet advanced for the alignment of the vents appears to be that based on a major fracture system in the earth's crust, the principal volcanoes arising at about equal distances of 25 miles, but not necessarily in successive order or at every point. The superficial fracture system has its major trend following the direction of the island chain on which are superimposed the secondary, divergent fractures arranged *en échelon*. That there are some deeper-seated lines of weakness on which the above system is superimposed appears probable, judging by the morphology of the arcuate groups of islands fringing the Asiatic continent and the more or less lineal chains of islands in Oceania.[12]

Two factors with regard to the relative age of volcanoes must be considered—the time of their beginning and the time of their extinction. The order of beginning, which may be judged only by the small summits of this range of lofty peaks projecting above sealevel, is a matter of conjecture, but is of interest in the above problem in its relation to the growth of the volcanoes progressively or irregularly along the major rift which underlies the islands. The volcanoes which built the original doublet Kauai were apparently contemporaneous. Western Oahu was carved almost to its present form before eastern Oahu robbed it of the moisture from the trade winds. Mauna Loa, on western Molokai, may have appeared before eastern Oahu, and the latter is of approximately the same age as eastern Molokai. Kohala and West Maui were probably contemporaneous and both may have become extinct before Haleakala, Hualalai, and Mauna Loa appeared. Hualalai and Haleakala ceased activity in historic time long after Mauna Kea became extinct, but both Hualalai and Kilauea were active before Mauna Kea ceased to grow and before the sea-cliff from Hilo to Kukuihale was cut to its present depth.

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[12] Prof. B. Koto has recently suggested that the "festoon islands" of Japan owe their origin and form to a major fracture system. Morphological summary of Japan and Korea, Jour. Geol. Soc. Tokyo, vol. 23, 1916, p. 172 (34).

While the spacing of the major vents suggests a progression of activity through each volcano in turn, the evidence observable on the summits of the volcanic piles, as just indicated, does not substantiate this suggestion.

Kilauea is here considered to be an independent volcano and older than its more lofty neighbor for the reasons given below. This conclusion does not prevent a sympathy in the activity of these volcanoes, as the evidence at hand favors sympathetic action, often very marked, but occasionally not especially noticed by observers in the past.

(1) The Kilauean sink is surrounded by pahoehoe flows, which may be seen in cross-section in the numerous fissures and faults found on all sides of the sink, and which may be studied in the Kau desert beyond the ash. The flows outside the sink are from one to three feet in thickness, like those within the sink, and the individual flows and festoons in the lava radiate from Kilauea, not Mauna Loa. The Mauna Loa flows, which have been pouring down the slopes of that mountain toward Kilauea, are largely thick, rough aa flows.

(2) The walls of Kilauea show thick and thin ash sections[13]; thin lava flows of very local extent, such as would not be expected in flows from the lofty slopes of Mauna Loa, and at least one unconformity,[14] due either to faulting or to erosion before the slopes of Mauna Loa diverted the rainfall from the summit of Kilauea east of the Volcano House.

(3) As seen from the vicinity of Punaluu and Honuapo, in Kau, the form of Kilauea clearly resembles that of the summit of Mauna Loa from a like distance.

(4) The signs of old age in Kilauea, with ash cones and pit craters on the Kau desert and on the eastern flank of the mountain toward Kapoho,

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[13] S. Powers: Explosive ejectamenta of Kilauea. Am. Jour. Sci., vol. 41, 1916, pp. 227-244.

[14] Idem, p. 230.

are more evident than those of the higher mountain. The pit craters can be duplicated on Hualalai, but the alignment along the course of the 1840 outbreak is lacking in the pits on the summit of Hualalai.

(5) Normal faults, as described below, bound the south shore of Kilauea and rift lines diverge from the summit of the mountain, showing the further breakdown of the old volcano.

Normal Faulting

Lines of weakness may be observed on almost all the islands of the group as features quite distinct from the wave-cut cliffs or from contraction cracks in lava flows or from the escarpments formed by the abrupt foot of a large aa flow. Commencing with Kilauea, the major structural lines may be described as they occur on each island.

Halemaumau, the summit sink of Kilauea, appears to have a direct connection with certain lines of weakness[15] which radiate from it: one extending down the Kau desert to the sea east of Pahala, and from which the flows of 1823 and 1868 issued (plate 29, figure 1); another extending from the prisoner's quarry north of the Volcano House toward Olaa; and probably a third extending from Keanakakoi and the Twin Craters past Puu Huluhulu, Makaopuhi, Heiheiahulu, and in the direction of the 1840 flows and of the Kapoho craters. Along these lines true rifts may be seen near the Kilauean sink, and in the case of the first line open fissures and faults formed in part in 1823 and 1868, but principally in prehistoric time, may be followed from Halemaumau to the sea. In 1868 a small graben or large fissure 30 feet in width and 40 feet in depth was opened from near the Kapapala ranch house to the sea and the pahoehoe flow issued from the head of the rift concomitantly with its formation. As the pahoehoe flowed toward the sea, on both sides of the opening, small rivulets flowed into the fissure, as shown in plate 29, figure 2.

A breakdown of Kilauea, previously mentioned by Hitchcock,[16] is found in the Keauhou pali, a series of cliffs south of the line of pit-craters and extending from Kalapana to the flow of 1823, a distance of 27 miles. On the west these cliffs, produced by normal faulting, are covered by the great number of flows which have poured down the southwest flank of the mountain from far back into historic time until 1868. Near the center of the faulted area, on the trail from the Volcano House to the Keauhou landing, a number of fault-scarps are traversed. These cliffs, over

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[15] First pointed out to the writer by Prof. T. A. Jaggar, Jr., and by Mr. H. O. Wood; described in part by C. H. Hitchcock, Hawaii and its volcanoes, Honolulu, 1911, pp. 108-109; Bull. Seis. Soc. Am., vol. 2, 1912, p. 190, and by H. O. Wood, Bull. Seis. Soc. Am., vol. 4, 1914, pp. 169-203.

[16] The Hawaiian earthquake of 1868. Bull. Seis. Soc. Am., vol. 2, 1912, pp. 188-189.

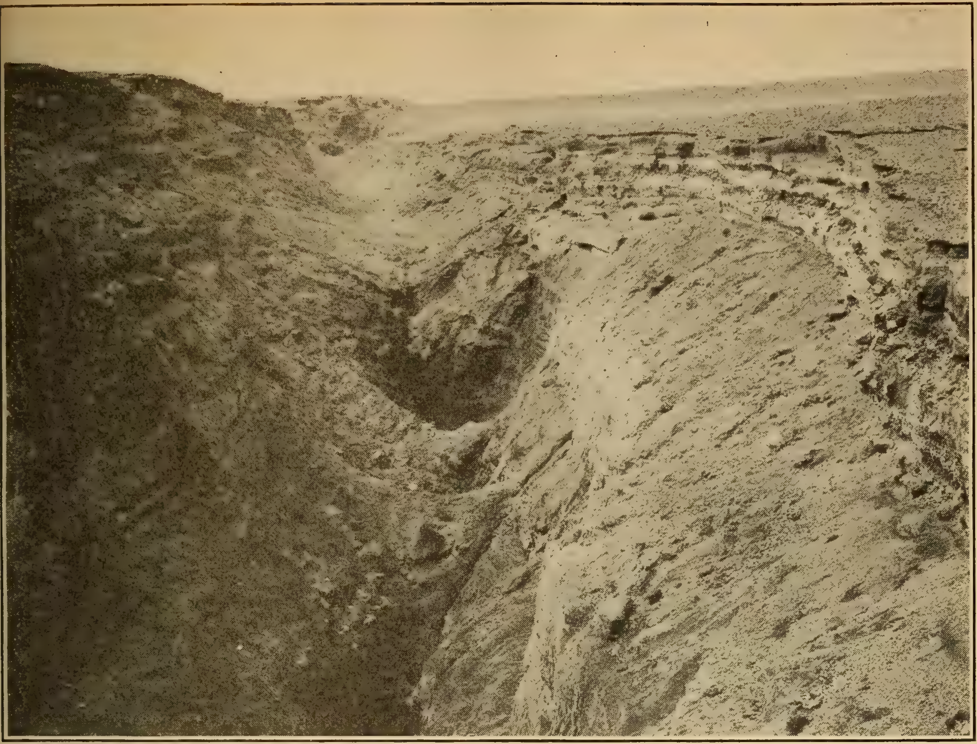

FIGURE 1.—ONE OF THE RIFTS IN THE KAU DESERT NEAR THE KILAUEAN SINK

The rift stretches in a southwesterly direction, seaward, with a downward displacement of 7 feet on the north side. Pahoehoe lava underlies the 10-foot ash bed and the deep fissures are in the lava.

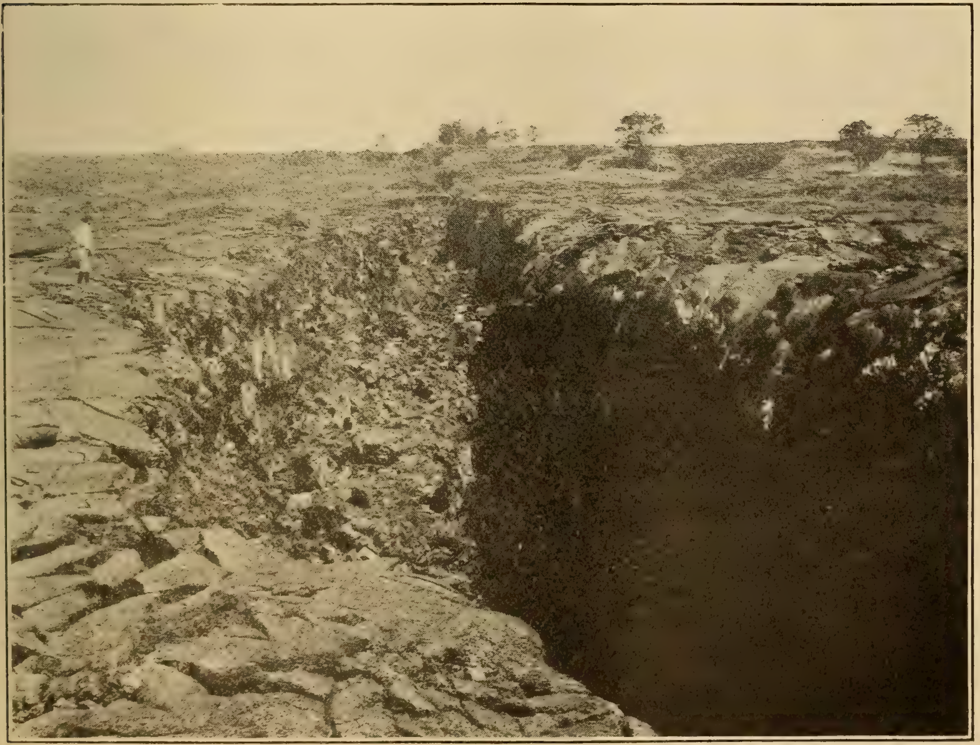

FIGURE 2.—THIS FISSURE OPENED IN 1868 NEAR PAHALA, IN KAU

View looking toward Kapapala. Into the fissure, which is about 30 feet in width and 40 feet in depth, the pahoehoe lava has trickled in a few small tongues only, although the flow covers the country for a quarter of a mile on either side of the opening. The fissure opened as the flow was cooling.

VOLCANIC PHENOMENA IN THE HAWAIIAN ISLANDS

which younger lava has poured in cascades, range in height from 10 to 1,000 feet and stretch along *en échelon* for many miles. One pronounced hill, Puu Kapukapu, 1,035 feet in height and not far from the Keauhou landing, either represents an old cone or a small horst which has persisted during the collapse of the mountain flank on all sides. The flat summit of the hill favors the latter mode of origin. In only one short stretch, just west of Keauhou landing, do high escarpments bound the shoreline.

Kalapana stands near the eastern end of the visible fault-blocks, although the same structures may extend farther east beneath the younger flows which, as at Pahala, have overrun the mountain slope.[17] The principal escarpment lies 2 miles northwest of Kalapana, but faulting on a smaller scale is observable at the village. This village is situated on a small plain partly submerged in 1868 and is faced on the west by a 10- to 20-foot fault-scarp, which is as fresh as if formed in 1868. The scarp is intersected by another of equal height which bounds the shore. These two scarps bound on the east and northeast sides a plain of which the Kalapana plain was evidently a part, judging from the distribution of a group of cocoanut trees northwest of the village, which is now half on each plain. The uniform size and distribution of the trees appears to admit of no other explanation than that they started to grow on a level surface which has been disrupted within the last century. Dr. W. T. Brigham sketched the Kalapana district in 1864.[18]

Catastrophic movements in 1868 which caused the southern part of Hawaii to vibrate almost continuously for several months had their center in a tectonic movement off the southern coast of the island, according to Mr. H. O. Wood's recent conclusions.[19] At the time of one of the most severe earthquakes the road near Waiohinu was shifted laterally 18 feet and the southern coast of the island in Puna and Kau subsided from 6 to 8 feet, with accompanying waves which destroyed a number of lives. Cocoanut trees and buildings were thus partially submerged and remained standing in the sea for several years before being washed away.[20] In this, the last important movement along the Kalapana-Keauhou fault-scarps, the Kalapana escarpment was certainly steepened, if not largely formed. A still later submergence along this line at Pohoiki, south of Kapoho, is said to have accompanied the earthquake of September, 1908.[21]

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[17] The youngest flow above Kalapana may be a branch of the 1840 flow.

[18] Mem. Boston Soc. Nat. Hist., vol. i, pt. 3, 1866, p. 373.

[19] On the earthquakes of 1868 in Hawaii. Bull. Seis. Soc. Am., vol. 4, 1914, pp. 169-203.

[20] An uplift of the southerly point of Hawaii between Honuapo and the Kahuku flow of 1868 is stated by W. L. Green to have apparently taken place and "the escarpment of (this flow) now forms the boundary of the lower part of the flow of 1868" (op. cit., p. 193). He also points out that on either side of this area, with a tendency to rise, are the recent lava floods from Kilauea and Mauna Loa. No such escarpment could be observed by the writer in sailing along the shoreline or from the beach at Kaalualu.

[21] C. H. Hitchcock: Op. cit. (1911), p. 263.

Mauna Loa is a vast mountain of basalt which has reached the stage where fountaining of very liquid lava takes place in the summit sink and flows break out on the sides, principally along two lines of weakness which are approximately parallel to the two best developed Kilauean lines of weakness. These lines are well marked at Mokuaweoweo, according to Dr. T. A. Jaggar, Jr., and the one extending to the south is marked by a fault-scarp extending from Kahuku, near Waiohinu, to the sea at Ka Lae, and attaining a height of from 800 to 1,000 feet near the sea. The displacement is down on the west side, and west of the fault the country is a waste of young lava flows, including those of 1907 and 1916. It was near this fault that a lateral shift of 18 feet took place in 1868, along a north-south line, the east side being moved north with respect to the west side. Another north-south fault-scarp is seen east of Waiohinu extending toward Naalehu. Whether the volcano was built up along the two lines of weakness which are now apparent is uncertain, but the elongation of the mountain in one direction is certainly toward Kahuku.

Elsewhere normal faulting occurred on the sides of Mauna Loa, for Kealakakua Bay is bounded on the north between Kaawaloa and Napoopoo by a fault-scarp which appears to continue, beneath a thick covering of later flows, south as far as Papa. Abnormal steepness of the mountain slope below the highway from north of Hookena to Papa seems explicable on no other grounds. Near Napoopoo a young flow cascades over the fault-scarp, as do flows over the Keauhou pali. At Honaunau, south of the City of Refuge, there is a low escarpment, overrun by a young flow, which possibly represents a parallel fault of small magnitude.

Mohokea, an amphitheatral depression in the side of Mauna Loa above Hilea and Pahala, has been described as a crater (or sink) comparable to the Kilauean sink.[22] It is 6 miles long from northeast to southwest and 5 miles wide. The depression is younger than the surrounding flank of Mauna Loa because the flows of that mountain are truncated in the walls of Mohokea. The floor of Mohokea slopes seaward and on the northeast side is underlain by alternating lava flows and ash beds.[23] Kaumaikeohu is a pointed hill rising at the entrance to Mohokea on the northeast;[24] Puu Iki rises on the northwest part of the rim, and Kaiholena, Pakua, and Makanao rise on the southwest. In the center is a row of conical and of flat-topped hills extending from Puu Enuhe toward Puu Iki. Near the entrance to the depression a number of flows have

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[22] C. H. Hitchcock: Hawaii and its volcanoes, Honolulu, 1911, pp. 149-153.

[23] S. Powers: Explosive ejectamenta of Kilauea. Am. Jour. Sci., vol. 41, 1916, pp. 242-243.

[24] An ascent of this hill, with the aid of a cane knife, revealed no rock exposures, but showed a fissure 6 feet deep crossing the northwest rim.

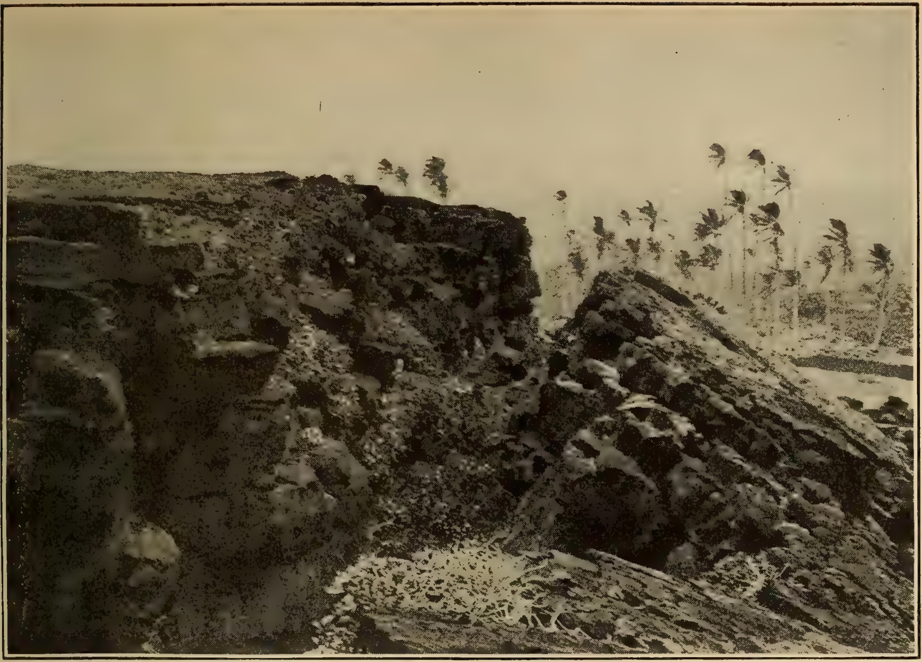


FIGURE 1.—THE 20-FOOT FAULT WHICH FACES THE VILLAGE OF KALAPANA, HAWAII
Showing in the distance the cocoanut trees, which also continue on to the higher faulted plain

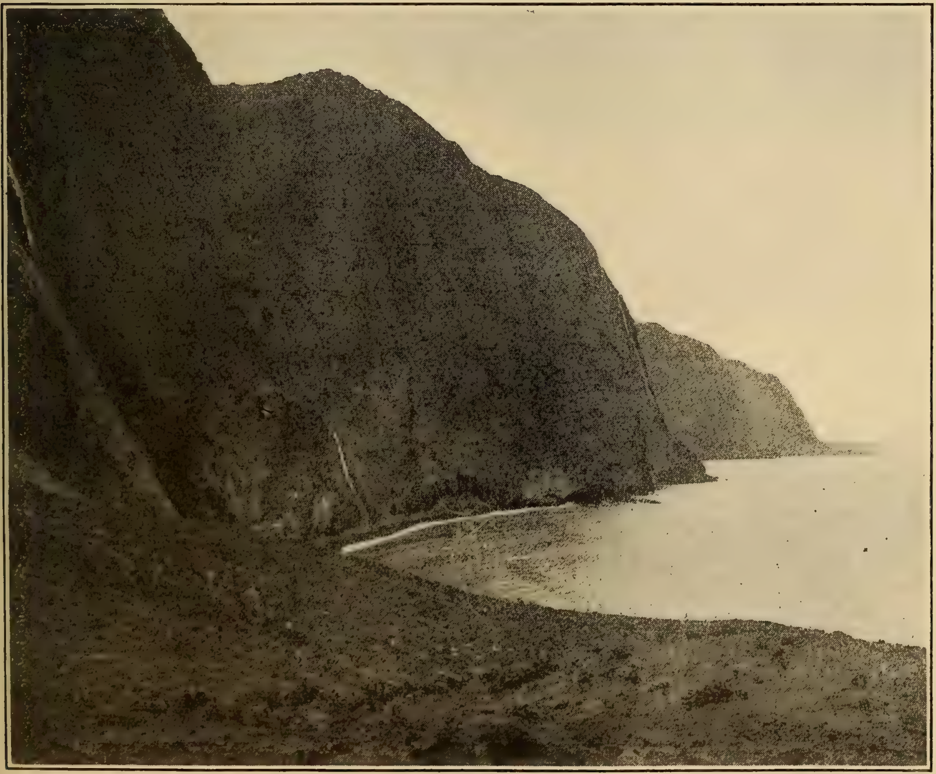
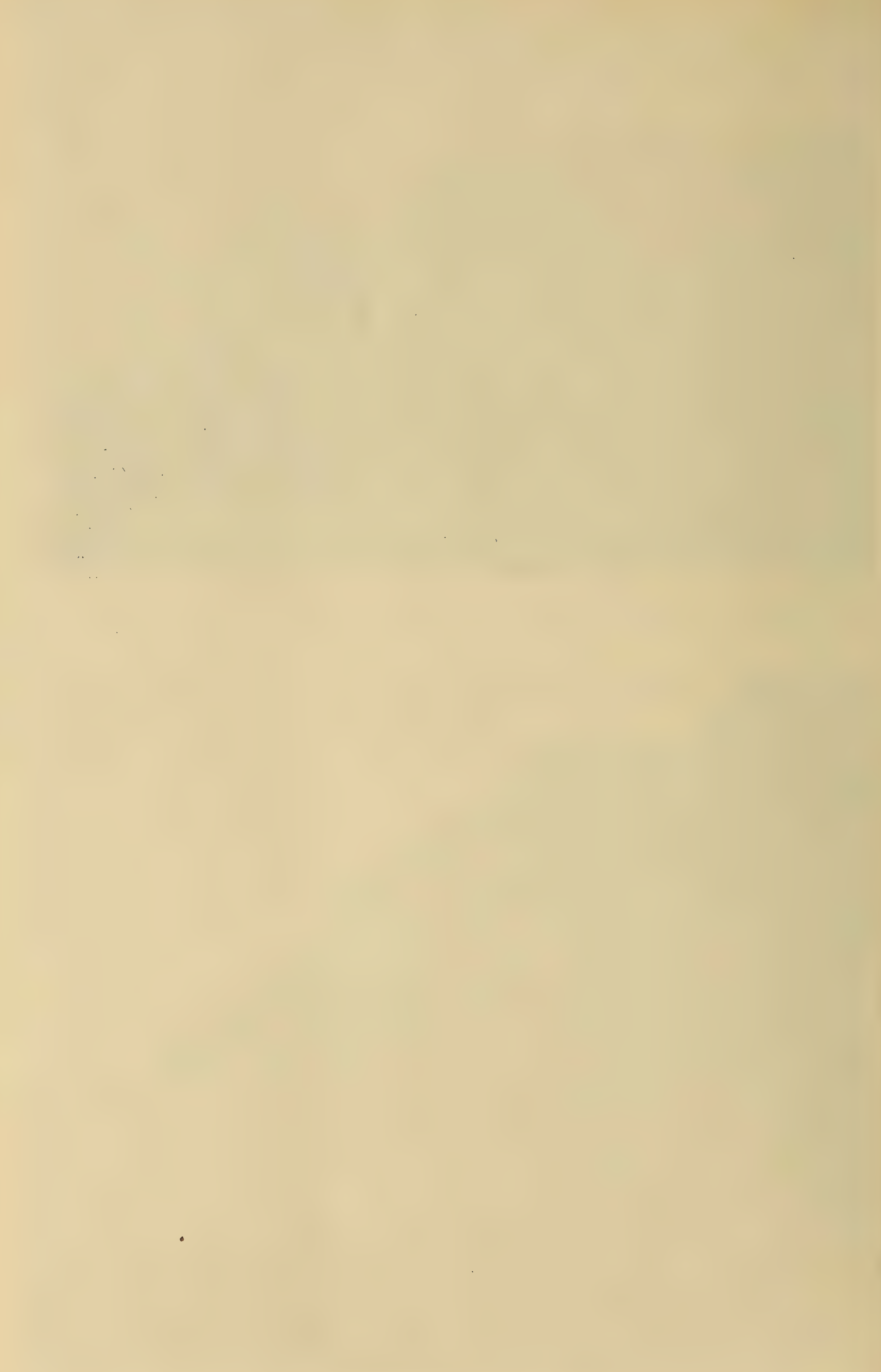


FIGURE 2.—FAULT-LINE SCARP
This fault-line scarp stretches from the landslide of 1908 near Waipio gulch toward Pololu gulch, on the northeast end of the island of Hawaii. The cliffs are 1,250 feet high

VOLCANIC PHENOMENA IN THE HAWAIIAN ISLANDS



[illegible]

covered the country between Hilea and Puu Enuhe, the latest of these flows being dated as 1868. Puu Kaumaikeohu and Puu Iki are probably cones, as they rise above the level of the surrounding normal mountain slope, but the flat-topped Puu Enuhe, Kaiholena, Pakua, and Makanao resemble horsts left by the inbreak of the amphitheater in a manner similar to the formation of the curved fault at Kealakakua Bay.

A fault-line scarp is traced by Professor Hitchcock along the southern boundary of Mohokea from the vicinity of Kapapala toward Waiohinu, but if this line of gentle escarpments represents a displacement of the lava flows, it must be a very old feature of Mauna Loa, long ago concealed by lava flows like those at Kilauea which have poured over the Keauhou palis in comparatively recent history.

Kohala is bounded from Pololu Gulch to Kukuihaele by a fault-line scarp[25] (plate 30, figure 2), and into the center of the old volcano the U-shaped valleys Waipio and Waimanu have been carved, while all the other valleys mounting at this fault-line are small. Even the largest of the smaller valleys—Pololu and Honokane—in no way compare in size with Waipio or Waimanu, although the amount of rainfall is approximately the same at the heads of all these streams. A quadrangular fault-block is suggested as the origin of the high plateau between the Waipio and Waimanu valleys and the fault-lines probably determined the course of these valleys. The lines of evidence supporting this conclusion are: the peculiar direction taken by the head of Waipio Valley transverse to the mountain slope and across the head of Waimanu Valley; the great depth of these valleys (both appear to be slightly drowned); and the fact that a cross-section from the summit of the Kohala Mountains through the block between Waipio and Waimanu compared with a similar section through the continuous mountain slope northwest of Waimanu seems to show an uplift of the block near its head.[26]

East Maui is well known because of the famous rent on the summit of Haleakala, the origin of which has been discussed by a number of geologists. The rent has a shape which defies description. The central portion, 5 miles in length, extends from the summit of the mountain eastward. The Koolau Gap (plate 31, figure 1), enshrouded in a tropical jungle below the 7,000-foot contour, extends from the center of the mountain northward, narrowing to the north. The Kaupo Gap extends from the east end of the central portion southward; and the Kipahulu rift, concealed by a jungle, stretches in an easterly direction from near the east end of the central portion and is really a continuation of that portion, but is completely separated from it by a comparatively narrow wall which effectually prevented exploration and even discovery for a number of years. The Koolau and Kaupo gaps, and especially the latter, are flooded by recent flows. The few men who have succeeded in going from the Koolau Gap into the Keaenae Valley to the sea report that the valley is composed of a series of amphitheatral depressions between the top of the mountain and the Ditch Trail, where there is a similar amphitheater 3 miles long and 1 mile wide. Down the head of this amphitheater waterfalls drop from heights of from 500 to 1,000 feet to the flat valley floor. Descriptions of similar structural features of the Kipahulu rift near its head are given, but near sealevel at Kipahulu there is no large valley (due perhaps to concealment by later flows), and one would never suspect the existence of the rifts far up the mountain slope.

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[25] First recognized by J. C. Branner: Notes on the geology of the Hawaiian Islands. Am. Jour. Sci., vol. 16, 1903, pp. 301-306. The submarine contours of 20, 50, 100, 200, 300, and 400 fathoms, as mapped by the U. S. Coast and Geodetic Survey, follow in notable fashion the recession of the shoreline along the scarp.

[26] Field observations were made from a triangulation station above Kaauhuhu and from the Hamakua ditch line above the head of Waipio Valley. Cross-sections were drawn from the new U. S. Geological Survey topographic sheets of the area.

Cross[27] argues that the Koolau and Kaupo gaps were formed by valley erosion rather than by block-faulting. If so, why does the Keanae Valley (Koolau Gap) grow smaller downstream when it heads in a trench so dry that no vegetation grows? The Kipahulu rifts are pronounced, according to authentic reports, near the Haleakala rent, and certainly the walls of the Kaupo Gap do not represent products of erosion.

Dana suggested that a triangular portion of the volcano had split outward or slightly subsided. If the former were the case, the corner of the triangular block opposite White Hill would have originally fit into White Hill, the summit of the mountain, and the sides of the Kaupo and Koolau gaps should roughly fit; but, at present, they would not so fit (even allowing for some faulting) if placed in the correct positions. In case the triangular block had subsided, the corner opposite White Hill should be appreciably lower than that hill (it is slightly lower), and the shoreline should not show outward displacement around the eastern side of the island. This shore is slightly protruding.

Another possibility is here offered: that the rents and the gaps were formed simply as graben similar to the ones which appear to have in large part made the magnificent Keanae and adjacent Honomanu valleys. In the heads of neither of these valleys is there any visible evidence of any splitting of the mountain as suggested by Dana. Somewhat in the manner in which the summit sink of Kilauea and Mokuaweoweo were formed, the Haleakala rent may have originated along perpendicular lines of weakness, while the portion of the mountain between the main trough

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[27] U. S. Geol. Survey, Prof. Paper No. 88, 1915, pp. 92-93.

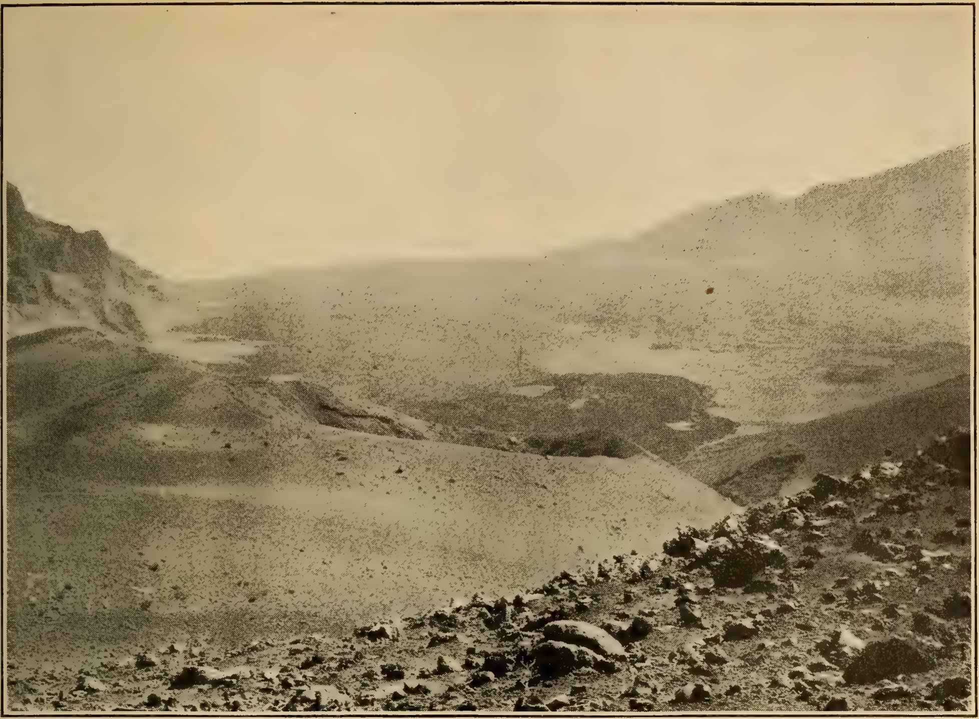


FIGURE 1.—KOOLAU GAP, ON THE SUMMIT OF HALEAKALA, EAST MAUI

This view is taken looking from White Hill over the lava flows which fill this portion of the summit rent and which extend over the edge of the gap toward the sea. The gap is three miles wide and the black lava flows are 1,300 feet below the camera.

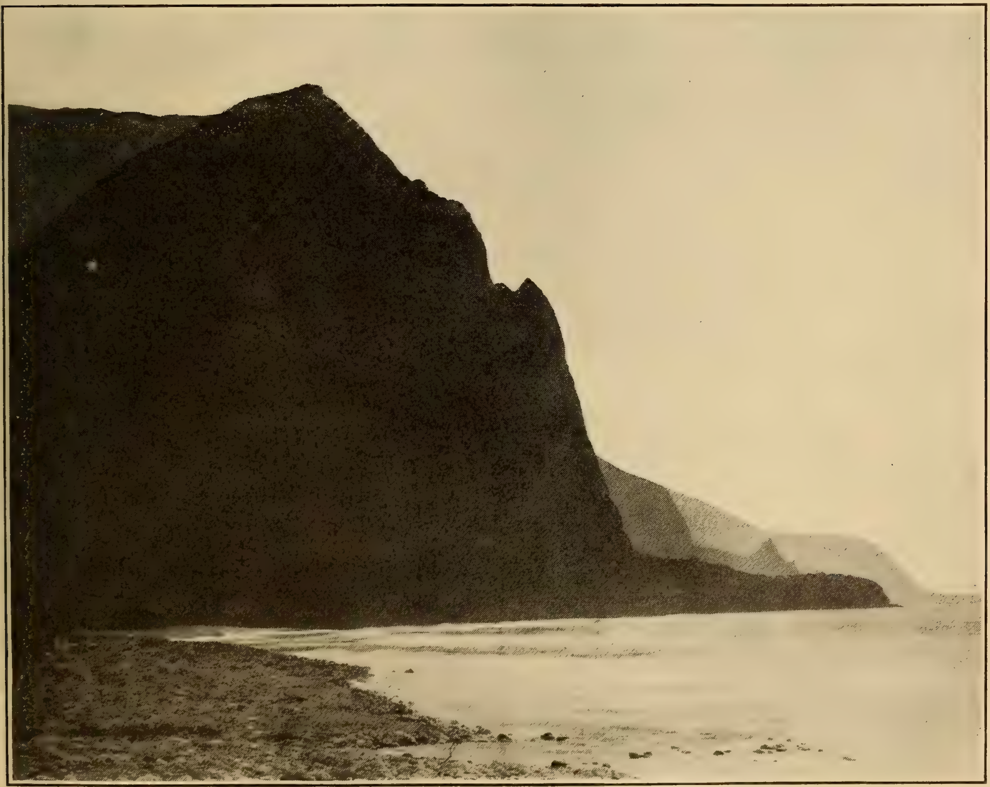
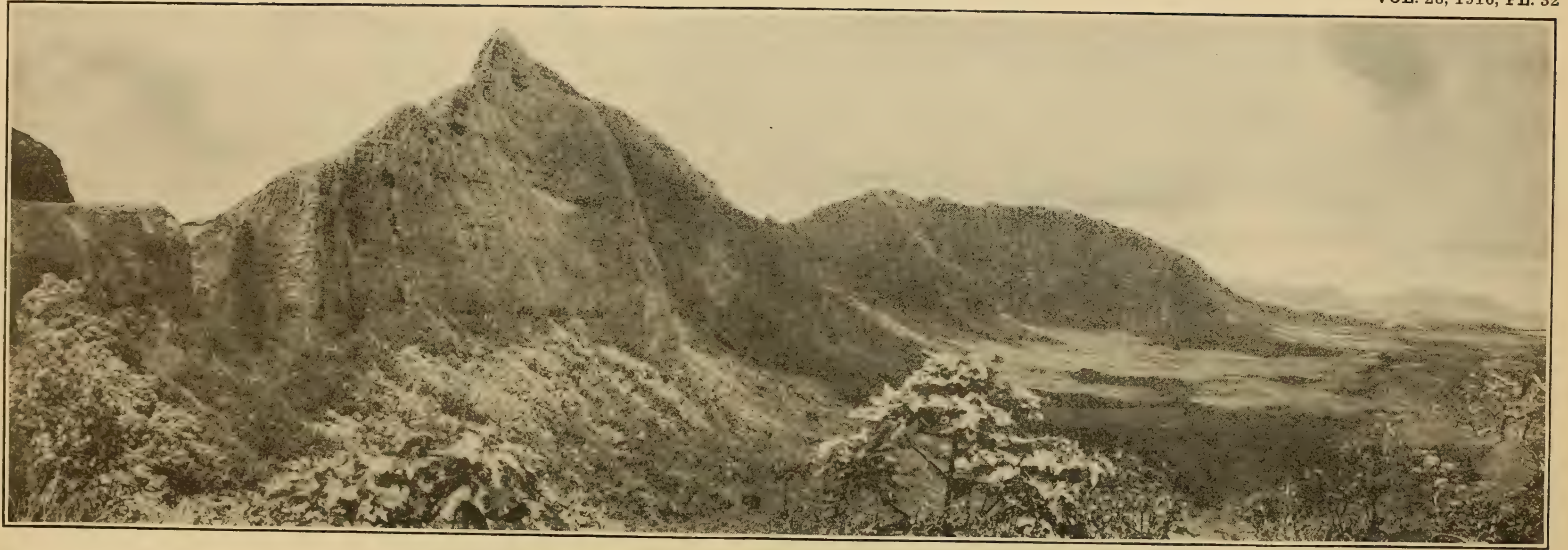


FIGURE 2.—FAULT-LINE SCARP BOUNDING THE NORTH SIDE OF MOLOKAI

Looking from Wailau gulch toward Kalaupapa leper colony. The peak is about 2,000 feet high

VOLCANIC PHENOMENA IN THE HAWAIIAN ISLANDS



THE PALI ON EAST OAHU, AS SEEN FROM THE SOUTH

The head of the Nuuanu Valley and the road over the Pali are seen on the extreme left. The northern end of the fault, along which these buttressed cliffs have been developed, is seen on the extreme right. The peak, Puu Lanihuli, on the left, is 2,775 feet high. Photograph by R. W. Perkins and the Kipahulu Gap remained intact. Normal valley erosion could scarcely produce the structural features described.

Evidence of faulting along the shorelines of Maui has not been observed, with the possible exception of the line of cliffs between Kaupo and Kipahulu, the ends of which are hid by younger flows. Similarly, on Lanai and Kahoolawe there is no indication of faulted shorelines.

On West Maui the Iao Valley and on West Oahu the Lualualei basin have both been described as calderas, although satisfactory evidence in support of this view and in opposition to the hypothesis of normal valley erosion has never been presented.

Molokai is bounded on the north by a fault-line scarp, as was recognized by Lindgren.[28] Two-thirds of the Wailau volcano[29] has subsided, leaving only a few crags projecting above the water not far from the fault-scarp (plate 31, figure 2). Kalaupapa, north of the fault-line, was formed from three centers of activity along a line perpendicular to the main fault.

Oahu presents a problem in the Koolaupoko district northeast of Honolulu where the pali wall stretches in a curved line from Makapuu Point to Waikane. Branner and others have argued that this pali (cliff) represents a normal erosion feature. The buttressed wall unquestionably shows the effect of erosion and Kaneohe Bay has been somewhat drowned, thus obscuring the drainage systems.

The wall, 23 miles in length, truncating the heads of the Nuuanu and other valleys extending toward Honolulu (plate 32), appears to the writer to represent a fault-line scarp buttressed by erosion. Such peaks as Olomanu and Manawili would represent crags of the original mountain mass which did not subside. The ridges extending out to Kualoa and Waikane would also represent portions of the original mountain, but the low ridges east of Kaneohe and the rounded hills now cultivated in pineapples may be eroded cones of younger age analogous to the ash cones at the head of the pali and the cones below the pali, both in the Nuuanu Valley and toward Kaneohe. These cones did not appear until after the major faulting, as is shown by the fact that the ashes from the cone at the top of the pali have covered a portion of the steep pali slope.

On western Oahu the Lualualei basin and the other broad valleys appear to have been cut by normal erosion before the Koolau volcano attained a sufficient height to rob the Waianae volcano of its rainfall. Drowning to a depth of over 700 feet filled these valleys with gravels and surface wash and obscured their original character. Lava flows in the sides of the Lualaulei basin do not dip away from this basin, but from a point near Kolekole Pass. Likewise, lava flows surrounding Iao Valley and Kilohana crater (Kauai) do not dip away from these areas, which are frequently called calderas and compared with the Lualualei basin.

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[28] U. S. Geol. Survey, Water Supply Paper 77, 1903.

[29] A name here proposed for the volcano which built east Molokai.

Kauai was originally composed of two volcanoes, as stated above. Dana, in his first visit to the islands, was the first to notice that the flows truncated in the Napali cliffs (plate 33) dip toward Waialeale; but he supposed that Niihau represented the missing volcano, moved southward.

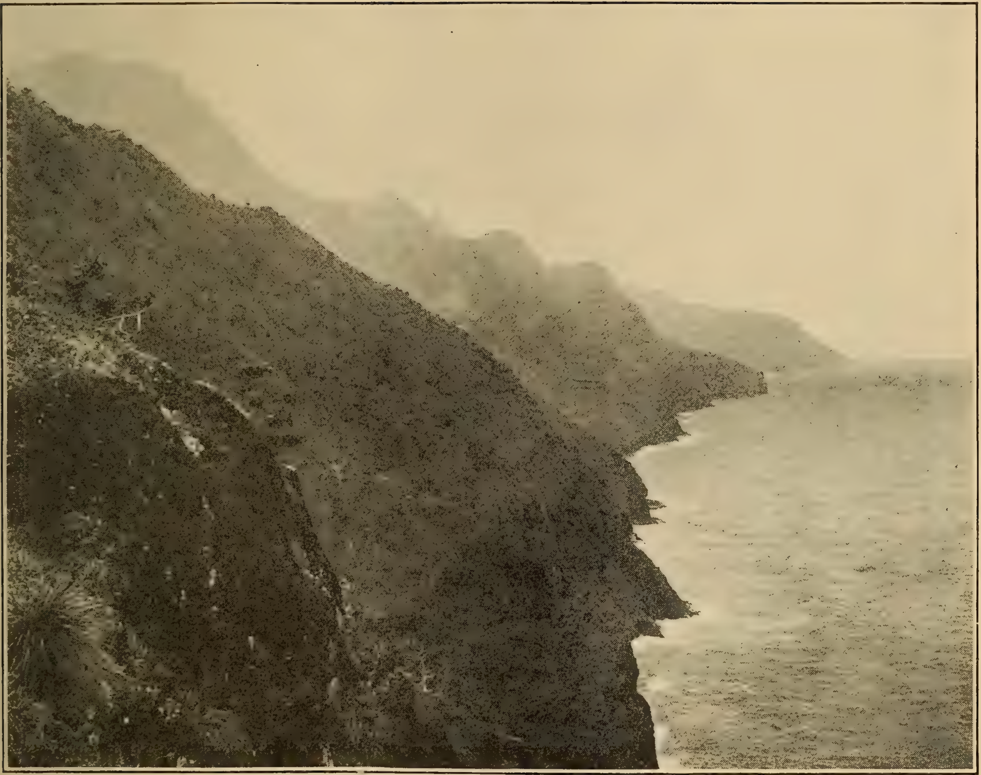
Niihau is so carefully protected from visitation by its owner that little is known concerning this desert island. The northeastern portion is bounded by a fault-scarp, along which the greater part of the original island has subsided; but this scarp is not a continuation of that at Napali.

SUMMARY

An examination of the hypotheses which have been proposed to account for the spacing of the volcanoes of the Hawaiian Islands has shown that the most plausible is based on a series of fracture lines which are part of a major fracture system. A remarkably uniform spacing of the vents has led to the suggestion that they have arisen in an orderly manner along two sets of fractures which comprise this system. The explanation of a rather definite arrangement of vents in purely volcanic islands in contrast to the frequent lack of arrangement in continental islands and on continents lies in the fact that the former have arisen from the deep-sea floor instead of having broken through groups of resistant rocks.

Along the Hawaiian rift the volcanoes have arisen not in exact order from west to east, but in a somewhat irregular manner, with a general migration of the lava in an easterly direction. Furthermore, the order of extinction of volcanic activity has not always been the same as the order of initiation. Evidence is presented to show that Mauna Loa is younger than Kilauea.

No connection has been found to exist between the lines of fracture now apparent in the islands with any other tectonic lines. While the growth of the volcanoes is dependent on the major fracture system and while there may be a sympathy of action between volcanoes during growth, the breakdown of each volcanic mass appears to be independent of that of any other mass. Normal faulting with the development of graben has been shown to offer an explanation for the structural features described.



THE NAPALI CLIFFS, KAUAI

These cliffs bound the northwestern side of Kauai, as seen from the vicinity of Haena, looking southwest. The mountain on the extreme left (Pohakea) is 3,355 feet in elevation

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 28, PP. 515-542, PLS. 34-35 SEPTEMBER 21, 1917

GEOLOGIC AND PHYSIOGRAPHIC INFLUENCES IN THE PHILIPPINES [1]

BY WARREN D. SMITH

(*Read before the Society August 5, 1915*)

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INTRODUCTION

From time to time scattered allusions to geographic, physiographic, and geologic influences in the Philippine Islands have appeared in the writings of Quatrefages, Gannett, Ratzel, Semple, and others, among whom the writer is included; but so far as the writer is aware no article has appeared which is devoted entirely to this most interesting field of research. The present paper is an attempt not adequately to supply the demand for this information, but simply to point out some of the most patent examples which it is hoped will serve to stimulate some one on the ground to follow up the subject with a comprehensive exposition. Perhaps too great a familiarity with the country—ten years spent in

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[1] Manuscript received by the Secretary of the Society March 12, 1917.
Read under the title, "Physiographic Control in the Philippines."

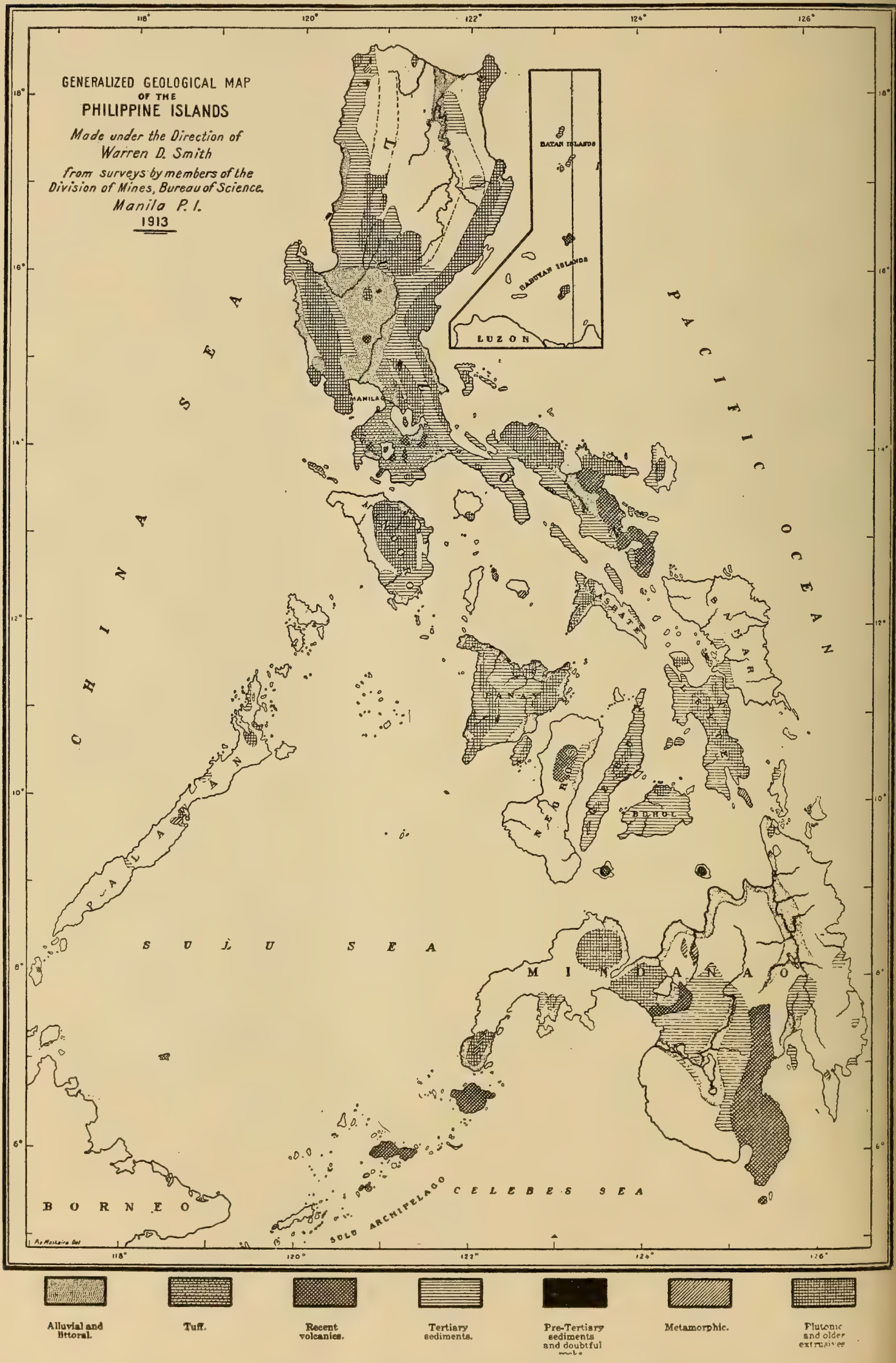

GENERALIZED GEOLOGICAL MAP
OF THE
PHILIPPINE ISLANDS
Made under the Direction of
Warren D. Smith
from surveys by members of the
Division of Mines, Bureau of Science.
Manila P. I.
1913
118°
120°
122°
124°
126°
18°
16°
14°
12°
10°
8°
6°
BATAN ISLANDS
BABUYAN ISLANDS
LUZON
MANILA
CHINA SEA
PACIFIC OCEAN
PALAWAN
SULU SEA
MINDANAO
SAMAR
LEYTE
BOHOL
PANAY
NEGROS
CEBU
MASBATE
MINDORO
SULU ARCHIPELAGO
CELEBES SEA
BORNEO
Alluvial and littoral.
Tuff.
Recent volcanics.
Tertiary sediments.
Pre-Tertiary sediments and doubtful rocks
Metamorphic.
Plutonic and older extrusives

FIGURE 1.—*Generalized geological Map of the Philippine Islands*

Used by permission of Philippine Bureau of Science travel and study in the islands, working mainly along economic lines—has caused to be overlooked here many important things which would occur to the trained geographer studying the problem for the first time. If the reader will look on this paper as an introduction to the subject and no more, he perhaps will not be too critical. It should be borne in mind, too, that the writer is primarily a geologist, and therefore the viewpoint of this article may differ from that of the geographer.

The same general groups of rocks exist in the Philippines as are found in other parts of the world. There are deep-seated igneous rocks, intrusions, and volcanic flows; there are metamorphic rocks, pyroclastics, and sediments, both consolidated and unconsolidated. The layman usually thinks of the Philippine Islands as almost entirely volcanic; nevertheless there is a wide distribution of the sedimentary series.

There is another essential feature of Philippine geology, namely, the striking similarity which exists between the formations in the Philippines and those of the west coast of America. The great basaltic and andesitic flows of the Pacific northwest can be duplicated, if not in size, in petrographic and structural characteristics, in this archipelago. Some of the Pacific Coast formations contain fossil forms not greatly unlike those found in the Philippines, and in many cases the lithology of the formations is quite similar in the two regions. The radiolarian cherts of the California and Oregon stratigraphic column also have their counterpart in these Islands.

Reference to figure 1 will show the distribution of the various formations. It will be seen that certain types of rocks predominate, at least on the surface, in certain parts of the archipelago; but this is due to no general law that we know of. Reduced to the simplest terms, the Philippine terranes consist of the sediments laid down on the Asiatic continental platform in Tertiary times, crumpled by crustal movements and in part broken through and veneered by igneous rocks of varying ages. In addition there are coral debris and aerial deposits which complicate the series.

The deep-seated rocks are not very widely distributed on the surface and usually are found only in the canyons of the central ranges. They are particularly abundant in northern Luzon, throughout the central Cordillera; in Palawan Island; the western Cordillera of Panay; the central Cordillera of Cebu and Leyte; the eastern Cordillera of Mindanao; on Masbate Island; in fact, wherever the streams have been able to cut through the overlying and more recent formations.

In all parts of the Philippines there is a large amount of extrusive material which forms a mantle over the deeper lying formations. Naturally these extrusions are found around the volcanic areas and are very pronounced in the Zambales Range of southwestern Luzon and in various parts of the Central Cordillera, lying above the old igneous rocks and the Tertiary sediments. The Central Cordillera of Luzon consists of great masses of andesite, probably marking Tertiary volcanoes. In the Zambales Mountains there is a development of andesite marking what is probably a still later period of volcanic activity. On Mount Arayat, which rises isolated out of the central plain of Luzon, basalt occurs, and also is found in considerable amounts around Taal Volcano and on the Binangonan Peninsula. Extrusives are particularly well developed in the volcanic cluster of southeastern Luzon, comprising the well known peaks of Bulusan, Mayon, Isarog, etcetera. They are found overlying much of Masbate, particularly in the central portion; also in western Panay, a portion of Cebu, most of northern Negros, central Leyte, and notably in Mindanao, there being a broad belt of extrusives running north and south through the Apo and Matutum ranges. There also is a patch of basaltic material around Lake Lanao, and a great volcanic mass of which Mount Malindang is the center. Great areas of these extrusives also cover almost the entire islands of Basilan and Jolo, and the lesser islands of the Sulu Archipelago.

As yet we know of extrusives in Palawan only in the northern part. The principal mountainous mass of Mindoro—Mount Halcon—is largely andesitic.

There is one general conclusion which may be drawn from the extrusives in the Philippine Islands, namely, that the entire recent volcanic activity, as far as we know, consists of basaltic ejecta, and the older stocks, without exception, are andesitic. The volcanic materials of the present vents are entirely fragmental.

Small and large intrusions of diorite, granite, and basalt are innumerable throughout the islands. In the Central Cordillera of Luzon the intrusions seem to be generally diorite. They cut both the Tertiary sediments and the overlying extrusives. In the province of Ambos Camerine, in southeastern Luzon, granite intrusions can be seen cutting the diorite and possibly the sediments. In the Sulu Archipelago there have been found a number of small basaltic intrusions cutting some of the recent sediments. Owing to the absence of an accurate base map of the Philippines and to the fact that our work has been largely of a reconnaissance nature, these intrusions have not been mapped in detail or with sufficient accuracy for us to state whether or not they follow any general system of jointing or earth lineaments.

Flanking all the cordilleras on both slopes there is a greater or less development of sandstones, shales, and limestones which have been bowed upward in the general Miocene uplift, with some minor crumplings at various points. It is not always apparent on what sort of surface these beds lie, though it is probable that they lie on irregular surfaces; at the margins of the older mass we find considerable thicknesses of conglomerates, the so-called "Agno beds" (from the river of that name) being typical. The folding in the northern part of Luzon apparently has been a gradual and gentle bending of the strata. In Tayabas Peninsula the flexures are sharper. In the Zamboanga Peninsula the strata have been so intensely compressed that schists are the result. These schists have been considered by some to be as old as the Paleozoic, but there seems to be no good reason for not referring them, in part at least, to the Tertiary. The central portion of Mindanao consists of gently folded sediments.

The major axis of folding in the Philippines is, in general, north and south; along the outside (eastern) arc of the islands it is northwest and southeast; on the inside (western) northeast and southwest, but in central Mindanao, in the Cotabato Valley, the axis of folding is more nearly east and west.

Metamorphic rocks, more or less pronounced, occur in various parts of the islands. In the province of Ilocos Norte there is a considerable occurrence of schist, and in Ambos Camerines there is schist and gneiss along the border of the granite intrusion referred to above. Schists have been found in one locality along the central cordillera of Cebu, at various parts of Palawan, on the Zamboanga Peninsula, in the province of Bukidnon, on the Surigao Peninsula and just east of the Gulf of Davao, Mindanao; at one point on the Tayabas Peninsula, and on the Caramoan Peninsula, southeastern Luzon. These schists, for the most part, appear to be metamorphosed sediments.

Recent alluvium from the mountains deposited on coral shelves results in a greater or less development of coastal plains around all the islands. The coastal plains, for the most part, are negligible, but some of the intermontane plains are very important. The northern three-quarters of the central plain of Luzon is largely alluvium, as is also the case in the Albay plain and the great valley of the Cagayan, Agusan, and Cotabato rivers. The central plain of Panay also shows a very considerable accumulation of detrital material.

Around Manila we have, in addition, a great area of pyroclastic material which is cut through by the Pasig River. From well-logs and river sections this is known to be at least 100 meters in thickness.

Each of these formations has resulted in a certain definite type of topography which naturally follows from the weathering and erosive agencies in any part of the world. In the Philippines, however, we have these agencies accelerated. This acceleration seems to depend chiefly on the following factors:

1. Excessive rainfall.
2. High mean annual temperature.
3. Great relief due to high declivity of streams.
4. Increased amount of chlorine, due in part to salt blown in from the sea.
5. Excess of vegetable acids.
6. Seismic disturbances.

In contrast to these degrading agencies we have the almost as important volcanic and diastrophic effects which tend, in part at least, to build up. The former is too patent to dwell on further than to say that a large part of the surface material is of volcanic origin in many parts of the islands. The increase of the land quantities by diastrophic movements is not so clearly seen, nor is it probable that it amounts to very much in any ordinarily reckoned period of time. The apparent elevation on the west coast possibly may be compensated by the very evident subsidence which has taken place on the east coast.

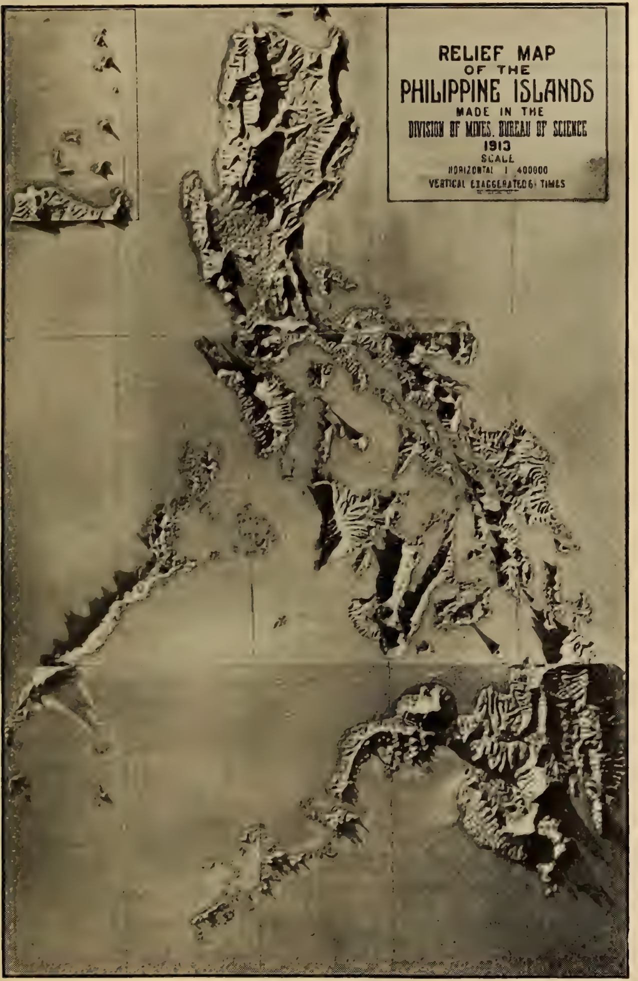
The salient features in the physiography of the Philippine Archipelago are:

1. The irregular configuration of the archipelago and the great mileage of the coastline.
2. Large development of mountains and the arcuate arrangement of most of them.
3. The proximity of the mountains to the sea.
4. Narrow and interrupted coastal plains due to the foregoing.
5. Five principal intermontane plains.
6. River systems which principally flow north.
7. Varieties of lakes and their origins.

IRREGULAR CONFIGURATION OF THE ARCHIPELAGO

The general outline of the Philippine Archipelago is suggestive of a giant sloth with Luzon for the head and shoulders, the Visayan Islands for the middle portion of the body, Mindanao for the pelvis, Palawan-Cuyo for the fore legs, and the Sulu group for the hind legs. The body of the animal appears as if it were inclined forward. But this analogy must not be carried too far, since the resemblance vanishes when we begin to look for the details of the skeleton.

The bulk of the land-mass lies east of the main portion of Luzon, the axis of that portion extending northwest and southeast at an angle not


RELIEF MAP
OF THE
PHILIPPINE ISLANDS
MADE IN THE
DIVISION OF MINES, BUREAU OF SCIENCE
1913
SCALE
HORIZONTAL 1 : 400000
VERTICAL EXAGGERATED 6 TIMES

RELIEF MAP OF THE PHILIPPINE ISLANDS

far from 45 degrees to the vertical. Extending southwest and at about right angles to this line are the two long arms of the Palawan-Cuyo-Mindoro group. South of this and parallel to it, but separated by a considerable stretch of sea, is the Sulu chain. The long axes of these groups have a northeast-southwest direction.

On the north we have the largest single land-mass, the island of Luzon; in the middle a larger number of much smaller islands, and to the south the second largest and more compact land-mass, the island of Mindanao.

A glance at a map of the archipelago will impress one with the most important single physiographic feature in connection with the whole archipelago, namely, the enormous length of coastline—11,511 miles in extent. This is due in part to the submergence of dissected islands—a condition of the whole land-mass comprising the archipelago. In addition to the great number of small islands, we find the larger islands liberally supplied with indentations of varying size, all of which increase the length of coastline proportionally.

It has appeared to the writer that there has been an elevation of the west side of the archipelago and a corresponding sinking of the coast on the east, both of which still are persisting. This belief is borne out by the raised beaches and coral reefs in places on the west coast of Luzon, the generally shallow condition of the mouths of the rivers debouching west, and by the presence of drowned rivers on the east coast—notably the Paracale River. As yet sufficient time has not elapsed, since accurate measurements have been made along the coast to enable us to say very definitely whether there has been much vertical movement, nor how much, nor in what direction. E. R. Frisbie, of the United States Coast and Geodetic Survey office in Manila, has noted a probable subsidence of the coast at Manila amounting to .31 foot in nine years.[2] United States Army engineers at Corregidor noted a slight elevation during a part of this period. Aside from the differential movement, there undoubtedly has been a general subsidence at times of the whole archipelago.[3] That there has been a corresponding and a very general elevation is borne out by the finding of fossil specimens of lowland vegetation at an elevation of 5,000 feet in north central Luzon.

It is the writer's belief that deeper water prevails on the eastern coastline than on the western. That this certainly is true a little distance out from the land is shown by the soundings of the German survey ship

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[2] E. R. Frisbie: Proceedings of Philippine Society of Engineers, Manila, 1911, p. 36.

[3] Fragments of corals have been brought in drill cores in the Batan coal fields from much greater depths than corals are accustomed to grow.

Planet, which located the deepest known part of the Pacific Ocean as being 53 miles northeast of the Mindanao coast, in 1910. This depth was reported as being 9,780 meters.

DEVELOPMENT AND ARRANGEMENT OF MOUNTAINS

The mountains of the Philippines lie generally in ranges that parallel the coastlines and which lie in close proximity to them. They are of two principal types: Those due to uplift with folding and erosion, and others due to vulcanism and more or less eroded.

The highest peak in the islands is that of Mount Apo, in Mindanao, of volcanic origin, which is 9,610 feet in height.

The most prominent chain of all is in Luzon—the Cordillera Central—which stretches from the northern boundary of the central plain to the Pacific Ocean, forming the backbone of this island. It is a composite of two, and in some places of three, parallel ranges, each of which averages about 6,000 feet in elevation. The highest peaks of this range, beginning from the south, are: Mount Santo Tomás, 7,240 feet; Mount Pulog, 9,400 feet—the highest peak on Luzon; Mount Datá, 7,360 feet, and Mount Amuyao, 8,857 feet. The range is largely intrusive and extrusive andesite, with sediments exposed high up on its flanks.

The Cordillera Central, as well as the two coast ranges of Luzon, may be said to be in that stage of physiographic development known as "topographic youth" or, in places, "early maturity." Hence the cross-sections of the stream valleys is "V"-shaped, which, however, may be modified to "U"-shape by the excessive talus accumulation from volcanic agglomerate cliffs above. Outcrops and falls are common along the main channels and there rarely are any great accumulations of wash in the stream channels, owing to the terrific scouring of the mountain floods.

In several localities, but especially in and around Baguio—the site of the summer capital of the islands—there is some plateau development. The topography of the Baguio plateau is strikingly like that of a glaciated region. The hills are rounded and veneered, usually with volcanic tuff, with scattered volcanic blocks, which at a distance resemble erratics, ponded drainage, etcetera. The writer at first was strongly of the opinion that he had found evidence beyond dispute that there had been glaciation in the highlands of Luzon. When, in the gullies, he came on deposits with angular blocks in hard clay, duplicating the general appearance of glacial till, he was almost certain of it. Fortunately he was persuaded by a fellow-worker, who had been in the tropics for a longer period—A. J. Eveland, formerly of the Philippine Mining Bureau—to ponder further the question of the apparent evidence of glaciation. This he did, with the result that he now believes that torrential wash in volcanic regions explains all the phenomena very satisfactorily. Even striæ were found on the rocks, but many of these "evidences" now are looked on with suspicion. The writer would here make a suggestion to all workers who think they see signs of glaciation in tropical regions, since evidences of glaciation have been coming forth rather rapidly of late from some slightly suspected corners of the earth: most of these undoubtedly are genuine, but some of the cases might be explained more simply.

Along the east coast is a range of mountains of which we know practically nothing. In places this range attains an elevation of 6,000 feet, but in the main it is much lower than the one first considered. It also is known to be largely volcanic in origin, having an active vent, Mount Cawa, near its northern extremity. This is a very sparsely inhabited part of Luzon.

Just northeast of the central plain these two ranges coalesce to form what Adams[4] has called the "Central Knot." This constitutes the highland country of Nueva Viscaya.

On the west, in northern Luzon, we find the Coast Range, known locally as the Malaya Range, which is narrow, but in places runs up to 6,000 feet or more. This also is andesitic, with some sediments found high up at various points.

In southwestern Luzon there is the Zambales Range, which consists of a line of more or less isolated old volcanic stocks in various degrees of denudation. The highest points in this line are Mount Pinatuba, about 6,000 feet, and the magnificent cluster of peaks known as Mount Mariveles, about 6,500 feet, at the entrance to Manila Bay.

In southeastern Luzon there is the altogether different type of mountain, a cluster of more or less recent dormant volcanoes, the commanding figure of which is Mount Mayon, a very perfect cone about 8,000 feet, near which is the city of Legaspi.

In the Visayan Islands we usually find only one cordillera to each of the small islands of which it forms the backbone. In Panay there are peaks in the cordillera over 7,000 feet, while in Cebu 3,000 feet is about the limit. The Negros cordillera is not so well defined, but has one dominating peak about 8,000 feet in elevation—the active volcano of Canlaon. Not much is known about the mountains of Leyte and Samar beyond the fact that there are some moderately high peaks of volcanic origin.

When we come to Mindanao we note an interrupted volcanic chain extending north and south in the central portion, in which are Mount Apo and Mount Matutum, the former, as stated, being the highest peak in the Islands, 9,610 feet. A cluster of peaks is irregularly arranged around Lake Lanao, and to the south of this lake there is the east-west line of dormant craters of the Buldun Range. The Malindang stock in northwestern Mindanao is nearly 6,000 feet in elevation, but has no great width. It forms the backbone of the Zamboanga Peninsula.

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[4] G. I. Adams: Geological reconnaissance of southwestern Luzon. Philippine Journal of Science, vol. v, pp. 2, 31.

From geological evidence it seems very clear that there was a general buckling throughout the archipelago. Where fissures opened along the crest of the folds vast quantities of extrusives poured out, concealing the underlying formations in many instances. Many of the islands, such as Cebu, merely are the eroded crests of the anticlines which appear above water with the straits between occupying synclines. The main crustal shortening took place in an east and west line, but cross-folding in the opposite direction also occurred.

It will be noted on the relief map, plate 34, that while the general trend of the mountain ranges is north and south, there is a bifurcation in the island of Masbate. From this point one set of lines extends, in the eastern part of the archipelago, in a northwest-southeast direction, and, in the portion toward Borneo, in the opposite direction. The two-pronged configuration of the island of Masbate is one of the most significant things about the whole subject. It is important to note also that at the intersection of these tectonic lines we have today the most productive quartz gold camps in the Islands.

As a rule, Philippine mountains are covered with dense vegetation, either with forest or with the ubiquitous cogon (Talahib) grass. But in some places, particularly well exemplified in the Zambales Mountains of western Luzon, there are forests near the foot of the ranges, and then, at from 3,000 to 5,000 feet elevation, the slopes are absolutely bare and rocky in many instances. Above this point, however, the well defined "mossy forest" covers the slopes to the summits.

While most of the mountains either are worn down volcanic stocks or more or less undissected cones, yet there are a few examples of the faulted and tilted block type. The latter are exemplified by those to the west of the railroad near Bamban, on the Manila and Dagupan Railroad in Luzon, and those on the eastern flank of the Cordillera Central of Panay. We shall consider later on how the mountain ranges have controlled the distribution and development of the various groups of peoples in the archipelago.

Mountain passes of the archipelago are:

a. O'Donnel-Iba Pass, in the Zambales, western Luzon.

b. Naguilian Trail, from San Fernando to the Baguio highland, north central Luzon.

c. Tila Pass, through the Malaya Range into Lepanto subprovince.

d. Balbalasan Trail, into the Kalinga highlands, northern Luzon.

e. Juan Villaverde Trail, across the northwestern corner of Luzon.

f. Infanta-Tanay Trail, across the rugged mountains east of Manila.

g. Atimonan Road, southeastern Luzon.

h. Tabuk Trail, in southern Mindanao.

In addition to these, there are many other shorter, but very important, routes leading through the mountains in the smaller islands like Panay, Cebu, etcetera. Some of the tribes make use of these passes, particularly the lowland peoples, such as the Ilocanos, who go up into the highlands to trade. But as far as the writer has had experience with the hill peoples, they seem to pay little attention to topography in traveling, almost invariably taking the shortest route, no matter how steep the trail may be. Our method of following contours does not appeal to them on first acquaintance. The lowland peoples do, however, pay some attention to topography. For confirmation of these statements the reader is asked to consult the census[5] map, showing the distribution of the various tribes. He will see at a glance how completely the paths of the Ilocanos, a coastal-plain tribe, criss-cross the country of the Igorot along the lines of least resistance—that is, by way of the lowest elevations. This also will help to explain the spread of some of the other tribes, such as the Tagalogs, from the region around Manila to the east coast of Luzon.

PROXIMITY OF MOUNTAINS TO SEA AND COASTAL PLAINS

As a consequence of the proximity of the mountains to the coasts, we would expect to and do find that there is little or no development of coastal plain, and that it is comparatively narrow where it does exist. However, with the steady growth of the coral platforms all about the coast and the contemporaneous deposition of great volumes of debris from the mountains, coastal plains are rapidly growing. The rainfall in this region on one occasion was almost the record for the globe, being 39 inches in 24 hours, as recorded at the Baguio Observatory, July, 1911.

The subject of torrential wash alone would furnish material for an extensive paper, but we can not digress at too many points in this paper. Suffice it to say, that these tremendous downpours, which carry enormous quantities of debris, profoundly affect the life of the people in these regions.

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[5] Philippine Census, 1903, vol. i.

One of the outstanding factors to account for the lack of coastal plains is to be found, as pointed out by Semple,[6] in the deep surrounding seas—that is, there is little or no shallow continental shelf on which alluvial material could accumulate.

A coastal plain more than 10 miles wide is an exception in the Philippines. Attention will be invited to this topic again because some striking practical conclusions may be arrived at.

INTERMONTANE PLAINS

A type of plain more important than the coastal is exhibited by those found lying between the mountains, and it is on these intermontane plains that the greatest development of civilization in the islands is to be found. The principal ones are:

a. Central Plain of Luzon.
b. Cagayan Basin, northern Luzon.
c. Central Plain of Panay.
d. Bicol Plain, southeastern Luzon.
e. Agusan Valley, eastern Mindanao.
f. Cotabato Valley, southwestern Mindanao.

As a rule, these plains have been formed by the aggradation of depressions between two isolated land-masses which were separated in Tertiary times. They generally are much wider than the coastal plains, though they have much the same origin and composition. With the exception of the Cagayan, they are broad and flat bottomed, holding the largest population of all equivalent areas. Cebu island is an exception, the people there living mostly on the coastal plain, there being no central plain and the interior having a high and rugged character.

For details regarding these important physiographic features the reader is referred to the specific descriptions in earlier papers on Luzon, Mindanao, etcetera, by the writer.[7]

RIVER SYSTEMS

As pointed out in the beginning of this paper, there are a few large rivers in the archipelago, but in the main the streams are short and swift. This is a natural consequence of the size of the land-masses and the youthful stage of the topography. The principal rivers in the order of their present importance are:

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[6] Influence of geographic environment, p. 446.

[7] Philippine Journal of Science, Manila, vol. i; Journal of Geology, Chicago, vol. xxi, no. 1, 1913, p. 29.

a. Pasig.
b. Cagayan.
c. Agusan.
d. Cotabato.
e. Rio Grande de Pampanga.
f. Bicol.
g. Abra.
h. Agno.

a. Pasig.—This is the shortest, swiftest, narrowest, and yet the most important of the island waterways. Its total length is not over 15 miles, having its source in Laguna de Bay and debouching into Manila Bay. The fall of this stream is slight, flowing as it does through almost flat country. While it does not carry the greatest volume of water-borne freight in the islands, it does transport the largest passenger traffic. In its lower part, within the limits of Manila, the river usually is choked with inter-island boats and launches. Vessels drawing over 15 feet never come into the river, only launches and very shallow-draught boats proceeding above Manila. The tide runs up this stream as far as Fort William McKinley, about 7 miles. At this point the river cuts through gently folded tuff beds, affording about 50 feet of section. This is important geologically because it gives an excellent opportunity for the study of the composition of the plain. This rock also is of considerable economic importance.

b. Cagayan.—This river is about 220 miles long, flowing from the south almost due north, save for its meanderings, and draining the extensive Cagayan Valley of northeastern Luzon, the great tobacco district of the archipelago. It is navigable for ocean-going vessels of shallow draught as far as the town of Tuguegarao, about 70 miles, and for boats drawing not over 3 or 4 feet as far as Echaque, 160 miles. The Cagayan unmistakably occupies a structural valley modified by erosion. Along its west bank the country generally is high because the river has swung over to that side of the valley. It is said that the dip of the sediments in the bluffs near Tuguegarao is westward, and it is quite likely that there is a fault-line which has influenced the position of the river. Professor Koto, of Japan, has expressed the opinion, verbally to the writer, that this may be a rift valley and a continuation southward of an important fault seen by him on the eastern side of Formosa.

c. Agusan.—This river likewise flows from south to north along a well defined tectonic line and is very similar to the Cagayan except that it is less open to navigation. It is navigable for launches only for a short distance above Butuan, about 25 miles, and beyond that only by native dugouts. It has one marked feature which sets it apart from the other rivers considered here, the large swampy tract composing the so-called lakes—Pinayat, Dagun, Sadocun, and Linao. These "lakes" are situated between Talacogan and Veruela, being really little more than a series of swamps. Tradition has it that the area subsided during an earthquake, giving rise to these lake-swamps in a manner similar to that of the formation of Reelfoot Lake, in Tennessee, United States of America. No authentic records of this event were found by the writer. The Agusan forms the only highway whereby one may travel for any distance in the province. The main article of commerce brought down it is hemp. The Agusan Valley is of rather recent origin, Pleistocene deposits being common along the river banks. The valley is, according to Maso,[8] the region of greatest seismicity in the archipelago. No active volcanoes are situated in or close to this region.

d. Cotabato.—Beginning in the extreme northern part of Luzon, this stream flows south until it reaches about the center of the island, at which point it makes a more than right-angled turn and continues somewhat north of west into Polloc Bay. It is the largest river of the island and is navigable for shallow-draught stern-wheelers for over 100 miles into the interior. The valley it occupies is wide and generally flat-bottomed, bordered by a rather marked escarpment on the southern side, which evidently was an old sea margin, being made up largely of coral material. The flat plain through which it meanders through several channels is one of the most fertile tracts in the archipelago, and it is here that the Government recently has established some large rice colonies in an effort to increase the productivity of the island and at the same time to colonize the island with Christian Filipinos. The main town on the river, situated on the south bank some 12 miles from the mouth, is Cotabato, which some day should be the largest city on the island, as it has what most of the Philippine towns do not possess, namely, a great and potentially rich tributary region to draw on. Above this there are only scattered Moro villages.

e. Rio Grande de Pampanga.—Rising in the "Central Knot" of the mountains of Luzon, the Caraballo Sur, this flows down the eastern margin of the central plain, very close to the eastern cordillera, and thence slightly west of south to Manila Bay. Its lower end breaks up into a network of canals, which anastomose with those of one or two other smaller streams that flow from the center and western margin of the southern half of this plain. In its lower portion it is a fine example of a "braided" stream. It is navigable for steamers of light draught as far as Mount Arayat, a distance of about 75 miles, and for rafts as far up as Cabanatuan, about 150 miles. For the most part this river is wide, shallow, with low mud banks. Just to the east and parallel to the river is the long and narrow Candaba swamp.

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[8] **Fr. Sadera Maso, S. J.: Bulletin of Weather Bureau, 1910, p. 283.**

f. Bicol.—This, the most important river in southeastern Luzon, rises in Bato Lake and flows northwesterly through the volcanic plain at the foot of Mount Isarog, emptying into San Miguel Bay. The most important town on it is Nueva Caceras, which is located at the head of navigation for ocean-going inter-island vessels. Above this town it is navigable for a considerable distance for flat-bottomed boats, especially in times of high water. In the uppermost regions a unique system of transportation is used, a dug-out towed by a carabao—a method due to the fact that the stream is exceedingly shallow in places, while in others it is much deeper. The lazy native finds it easier to be towed by his animal than to propel the boat by poles, especially since the carabao can swim in the deeper places and does not mire down in the shallow, muddy reaches where he walks.

g. Abra.—Rising on the flanks of Mount Datá, in north-central Luzon, the Abra flows west for a short distance before it turns northward—in the tectonic valley to the east of and parallel to the Malaya Range—almost as far as the town of Dolores, where it turns sharply to the west. From this point it proceeds in a south-of-west direction and breaks through the coast range just south of Vigan. It is navigable only for rafts and dug-outs. From the situation of this stream and some of its tributaries, it is the opinion of the writer that the Abra is a captured stream, and that formerly there was a more important watercourse of greater length which followed the Abra Valley, though possibly much farther north, and that it may even have debouched near Laoag, many miles to the north of Vigan. A good atlas map of Luzon will show the location of most of these points.

h. Agno.—This stream also rises on the flanks of Mount Datá, but flows south in another structural valley and debouches onto the central plain of Luzon. Due to warping of this plain, the river makes a great sweep and turns to the northwest, emptying into Lingayan Gulf by way of a series of smaller channels. It is practically entirely unnavigable, but is worthy of consideration because of the great destruction caused when it floods its banks, as happened so disastrously in the rainy season of 1911. At that time almost the entire country from Moncada to Dagupan was under water, and in places the flood rose nearly to the tops of the telegraph poles. At the same time an important new dam and irrigation project which the Government was building was almost completely obliterated.

LAKES

There are several different types of lakes to be found in the Philippines. The most common are those which are little more than deepened swamps; second, those formed by a local widening of a river; third, those due to a damming up of a drainage basin; fourth, explosion crater lakes; fifth, those due to local subsidence of the land.

Of the first type we have Lake Bato, in southeastern Luzon; Lakes Liguasan and Buhian, in Mindanao. Of the second are Lake Canarem, in the Central Plain of Luzon, and Lake Bito, in the eastern part of Leyte. The best example of the third is Laguna de Bay, near Manila, while Lake Lanao is another of this type. There probably are several explosion crater lakes, but the best known is Laguna de Bombón, also known as Lake Taal, situated about 35 miles due south of Manila, while other examples probably are Laguna de Manjan, in the northeastern part of Mindoro, and several smaller ones on the islands of Sulu and Cagayan Sulu. Among those illustrating the subsidence type are the Agusan lakes—Pinayat, Dagun, and Linao.

It very probably is true that many of these lakes have originated through the operation of more than one of the causes enumerated, as in the case of Laguna de Bay, which may have been formed through subsidence in part and also by a barrier of arched tuff beds being elevated between this low strip and the sea.

To consider in detail the examples under each type:

Lake Liguasan.—In the dry season this is little more than a great swamp, which the rainy season transforms into a large lake. It covers many miles of territory just south of the point where the Rio Grande de Cotabato changes its course from south to northwest. In fact, this body of water is connected by a maze of shallow channels with the river, and also with another but smaller lake to the south, known as Laguna de Buluan. These two lakes have important Moro settlements on their shores, since they afford good fishing and hunting grounds, as well as cheap means of transportation. The surrounding country is low and excellently adapted to rice growing.

Lake Canarem.—On the old Jesuit maps of Luzon this lake is shown as a coalescing of several tributaries, and, strangely enough, according to the maps, water seems to flow into it from almost any direction, and out of it either toward the Agno—north—or toward the Pampanga—south. The area covered by this lake is only about 25 square miles, but it is a good example of the extended river type.

Agusan Lakes.—These four lakes, situated about half way between the source and the mouth of the Agusan River, which flows through them, are apt to coalesce into one big lake in the rainy season. According to tradition, they were formed during a local subsidence of the valley. This seems to be confirmed by the fact that this region is marked by the greatest degree of seismicity in the archipelago. Those who have traveled up this river report that there is a bewildering network of channels connecting these lakes, and that the whole area resembles a vast swamp in which the water has risen far up on the trunks of the trees growing in it.

Laguna de Bombón.—This lake, which may be likened to Crater Lake in Oregon, United States of America, has been studied by several geologists, but particularly by G. I. Adams, formerly on the staff of the Division of Mines of the Bureau of Science, Philippine Islands. As his views appear to the writer to be as satisfactory as any yet expressed, and as he incorporates in his discussion the important statements contributed by previous writers, the following quotation is made from his paper:

> "Taal Lake is evidently a caldera formed by peripheral and radial faulting and the subsidence and collapse of the many cones which have been formed within its area during prehistoric eruptions. The process of formation has been continued to a small degree during historic time.
>
> "The fact that the caldera is occupied by a lake prevents in a large measure the study of its origin. However, in the brief notes concerning the two eruptions of Taal, it is recorded that within Taal Lake a new cone arose as an island and subsided, leaving as its remnants two small islands which lie to the east of Taal Volcano. In another eruption a portion of the shore of Taal Lake near the former site of the settlement of Taal subsided below the water. Many who see the sheer face on the west side of Mount Macalod form the opinion that a large mass of the mountain has subsided into Taal Lake, and as substantiating this idea it is pointed out that the deepest part of the lake is found near this mountain. While studying the shores of the lake it was observed that in certain parts they are precipitous, while in others they are eroded into gentle slopes. It may be that some of the precipitous shorelines are due to recent faulting and displacement, but it will require a detailed study to prove this." . . .

The evidence for Adams' conclusion can not all be given here, but the two most important points are the existence of faulting in the region surrounding the lake and the shape of the profile of the country along a line drawn through the center of the lake. The consensus of opinion among geologists who have studied the lake (the writer is of this number) is that a combination of circumstances—explosions, subsidences, etcetera—caused the present condition of things—that is to say, that this lake and Crater Lake in Oregon might not improbably have had very similar histories.

Taal differs from Crater Lake particularly in the matter of elevation. The former is only 2 or 3 feet above sealevel, while the latter is nearly 8,000 feet above. Taal Lake has an active volcano in its center, while the Oregon lake has not. The coloring of Crater Lake is much finer than that of the Philippine lake.

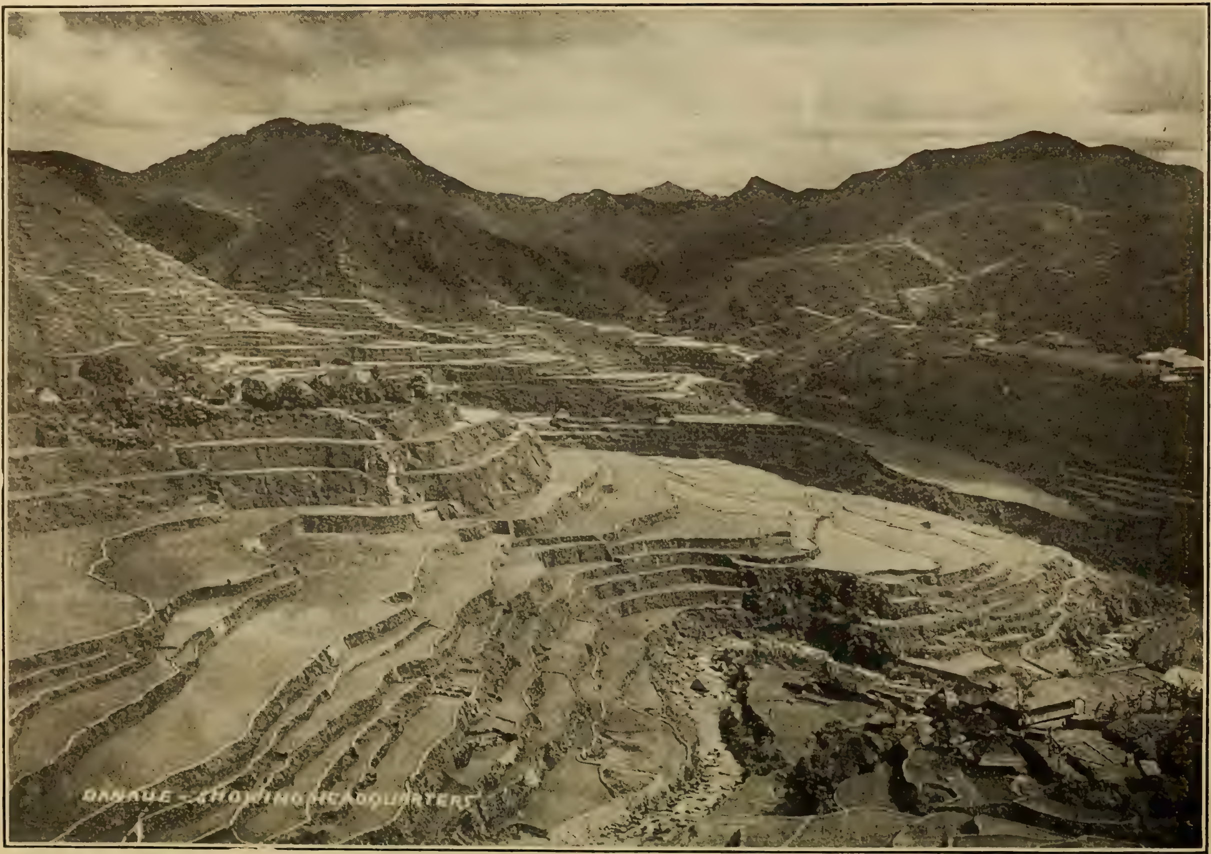
There are many smaller calderas occupied by water in the region where

Taal is located. These are particularly numerous and a prominent feature of the topography in the vicinity of San Pablo, Batangas. Many of them are perfectly circular and of unknown depths. They are of various dimensions, some being only a few yards in diameter.

Laguna de Bay.—This is the largest lake in the archipelago and the most important in the life of the people of the islands. The greatest length and width of water are 25 and 21 miles respectively. It is quite shallow throughout. The contour of this body of water is perhaps the most characteristic thing about it, being roughly heart-shaped and having three prongs or fingers projecting northward. It seems probable that this lake covers a stretch of low country once occupied by the sea, the latter having been cut off by the deposition of a great amount of tuff, and the later gentle folding of these tuff beds forming a dam on the western side of the depression. The slightly arched tuff beds can be seen plainly where the Pasig River cuts through them near Fort William McKinley. The high land on which the post is situated is due to the bowing up of these beds. The fact that this lake formerly was occupied by an arm of the sea was proved to the writer's satisfaction by the finding of suggestions of marine terraces on Binangonan Peninsula. Adams was unable to see these, and also cast some doubt on the evidence produced by the finding of recent marine shells on some of these benches. It is admitted that these shells may have come from kitchen-middens, as Adams suggests, but the marine terrace theory seems more correct, since the latter alone will satisfactorily account for the presence and appearance of the benches. In a region of excessive rainfall terraces would not be as well preserved as in more arid regions.

Around the eastern shores of the lake, on the Jala Jala Peninsula, and on Talim Island, there is considerable basalt in the form of flows and agglomerate. The shape of the lake suggests former well defined north and south valleys, whose width, shape, and extent have been modified by these flows and tuff deposits.

Lake Lanao.—This lake, 15 miles in length by about 12 miles wide, is situated at an elevation of 2,250 feet above sealevel, in the upland of northern Mindanao. It is roughly bell-shaped and is supposed to be very deep. The writer is of the opinion that it is not a crater lake, as many have supposed, but has originated through the damming up of the headwaters of the Iligan River by a basalt flow and loose material which has come down from the mountains on either hand. A noteworthy feature of the topography of this lake country is the Keithly escarpment, on the south shore of the lake. The abrupt slope of this topographic feature is away from the lake. No big cuts were found in this ridge, so no judgment of its composition was possible; but the inference from what could


BANAUE - SHOWING HEADQUARTERS

RICE TERRACES OF THE IFUGAOS OF NORTH CENTRAL LUZON be seen on the surface is that the material in it is fragmentary. Lake Lanao is noteworthy as being the principal stronghold of the Moros in Mindanao. The lake is surrounded by high mountains some distance back from its shores, but there is much fine agricultural and grazing land near its margin.

Human Response to physiographic Conditions

Some of the more prominent illustrations of physiographic influences on humanity in the case of the Philippines are:

The principal and most advanced population is found on the great central plain of Luzon. At the lower end of this plain, where the Pasig River enters Manila Bay, is located Manila, the largest city of the archipelago. The location of the metropolis is controlled absolutely by the juxtaposition of sea, plain, lake, and river—a combination such as is found nowhere else in the archipelago. The Tagalogs happened to be living at this place when the Spaniards came, and to this accident must be attributed their present political ascendency over the other tribes rather than to any inherent qualities possessed by them.

Although the outside world hears most about the Tagalogs, it is the Ilocanos of northwest Luzon who have impressed the writer as being in many ways the most energetic and thrifty of all the tribes of the islands, and it is this tribe which, according to the census figures, is expanding at the greatest rate. Here seems to be an especially fine illustration of the influence of geographic position. The Ilocanos live on the narrow coastal plain in that part of Luzon nearest to China. Historical records show that the Chinese trader and sea rover touched at Ilocano points first, and wherever the Chinese came in contact with the Filipinos the latter was improved thereby. The basic agricultural practice in the islands today is of Chinese origin, but the best improvement wrought is in the advancement of the race through intermarriage. Of all the mestizos (mixed bloods) the writer considers the Chinese mestizo as by far the best. As we are not engaged here in an ethnological discussion, we must leave this assertion for some one else to affirm or refute, as the truth of the case demands. The writer believes that the geographical point can not be questioned.

The present condition of civilization of the tribes of north-central Luzon is to be attributed primarily to the nature of the country which they inhabit, this having served to break them up into isolated groups and to keep them so. The political and cultural unit in this region is the village, and the size of the village is dependent on the amount of irrigable land in any one locality. The general inimical feeling which existed until recently between the peoples of different towns was due almost solely to the lack of contact, and the latter is to be attributed to the absence of easy communication. In fact, almost all of the tribal differences today in the archipelago, as in many other parts of the world, are due to isolation. It is noteworthy that a prominent and highly educated native ex-official in the islands, himself a low-country Filipino, said that he saw his first Igorot at the Saint Louis Exposition.

The Igorots furnish an excellent example of the influence of topography on a people.[9] While much has been written about this tribe, no attempt other than that by Jenks has been made, so far as the writer is aware, to get down to the underlying causes of their local differences and their peculiar modes of providing sustenance for themselves. The basic factors in the life of a people, from the Occidental standpoint at least, are economic. It is well known that the Igorots have put into operation a notable system of irrigation. Its origin is not attributed to the Igorot himself, for it seems quite probable that the Chinaman taught him, but he does use it, and that remarkably effectively. While in some parts of the low country the Filipino is nearly starving for want of rice, his highland brother sometimes raises three crops a year of the same article in a country very difficult to prepare for a crop of any kind. It is not necessary to describe the Igorot's system of irrigation here, as that already has been very well done by Jenks and Worcester. Some idea of it may be gained from the photograph, plate 35.

Some of the physiographic and geologic factors which have produced the kind of civilization now to be found in north-central Luzon may be enumerated as:

a. Altitude.
b. Rugged topography—extremely accentuated relief.
c. Absence of navigable streams.
d. Distance from the sea, the greatest natural highway.
e. Vulcanism.

Altitude has given the highlander the energy which sets him apart at once from the low country plain dweller. Rugged topography has prevented the formation of large natural dwelling groups and has accentuated the family and village life. Absence from natural streams and distance from the sea, the oldest highway, have kept these peoples from traveling very far from home. The last-named factor, vulcanism, as manifested by fumaroles, hot springs, etcetera, has helped to make him more superstitious and to inspire awe of natural phenomena. That the system of irrigation and the raising of crops on terraces on steep hillsides is directly referable to the natural topography is clear. Not only must these people work very hard, but they must work practically *all* the time to wrest a bare subsistence, there being little game in the country, which is another important reason why the various communities do not mingle more than they do. Therefore the policy of the Government in affording communication by means of trails and roads is of paramount importance in the bringing together of these isolated groups.

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[9] A. E. Jenks: The Bontoc Igorot. Ethnological Survey, Philippine Islands, vol. i.

In passing through the country lying east of Bontoc and south of the Cagayan Valley—the "No man's land" referred to by Worcester—the writer was struck by the generally impoverished condition of the people to be found there. They live in extremely small and scattered communities, in squalid surroundings, with both mongrel customs and mongrel dialect—the so-called "Gaddong." If the character of the country is noted the explanation is apparent. The underlying formation, sandstone, is not such as to yield the most fertile soil, even though it is a soil made up of triturated fragments of volcanic formations. In the second place, the country is characterized by swales and hummocky hills, with little forest. This section is not inaccessible and consequently there is some mingling with the lowlanders, though this does not appear to have wrought any improvement in the inhabitants. This apparent contradiction to foregoing remarks may be explained by the fact that the means of intercommunication are just difficult enough to bar any from going backward and forward except the most adventurous and unscrupulous, and so the hill man often is exploited without being materially benefited by contact with outsiders. This region well may be the rendezvous of the inferior and vicious elements driven out of the surrounding sections.

The island of Cebu and its people furnish still another fine example of physiographic influence. Here is to be found the most congested population in the archipelago. It practically is confined to a narrow and interrupted coastal plain which has no productive hinterland—only a rugged mountainous interior.

It was on this island that the Philippine Government caused to be constructed what at the time was a wholly unnecessary railroad. Fortunately for the company which built the road, the Government guaranteed 4 per cent on the investment; but even a superficial knowledge of the physical geography of the island should have warned against the venture. The population, a poor one, lives close to the sea, the cheapest highway in the world. Parallel to this is a macadam road, and there was no call, as there seems to be none today, for a railroad which runs for most of its length parallel to and within a few feet of the two highways already existing.

The reason for the excessive population of Cebu in proportion to its area of arable land is not known. Perhaps the Visayan is more fecund than other tribes. The density of population of Malay islands may partially be explained, as Semple[10] says, by two facts: "The attraction of the coast for the seafaring Malay race" and "the mathematical law of increase of shoreline with decrease of insular area." This does not always hold, since Mindoro is far smaller than Cebu and has less people, even proportionately, but in the main is an explanation which will hold.

The island of Panay offers another instance of physiographic control. The Negritos, a backward and vanishing tribe, are located in the most inaccessible parts of the cordillera. A second group, known as the Montescas, live in the rugged and unproductive intermediate uplands, while the more progressive Visayans inhabit the plains. But even in the case of the last named there is a difference in dialect between those living on the Iloilo plain and those north of the upland barrier, which connects the cordillera with the low mountains in the eastern part of the island.

In the Philippines there seems to be found at least a partial confirmation of the dictum laid down some years ago by a student of history to the effect that land-masses more often have been a barrier to migration than have the oceans. Very often there are found people more alike on opposite sides of a stretch of sea than those living in different parts of the same island or land body. There is more homogeneity in the peoples of the Visayan Islands than among those living on Luzon. This is what would be expected, however, in the Malay region, where the people live largely on and by the sea. The inhabitants of the Sulu Archipelago are more closely related to those of northeast Borneo than they are to the Visayans or the Tagalogs of the Philippines.

The stronghold of the Moros in Mindanao today is in the Lake Lanao country, while there is a flourishing settlement of theirs about Liguasan Lake. As they spread inland, or are driven there, as the case may be, they congregate in those places where they can live as nearly as possible according to their old habits. They are found on the lakes, with the fish traps and gaudily colored sail-boats ("vintas") as if they still were on the sea.

The location of highways in the Philippine Islands probably is the best instance of the influence of topography on the affairs of white men, a notable example being furnished by the famous Benguet Road. Here was a project which seemed feasible and satisfactory from every point of view, but the factors of topography, precipitation, character, and structure of the rocks controlled absolutely. The nature of the rock, badly weathered andesite, in the canyon walls alone was enough to condemn the undertaking. As originally laid out the road is a failure, and we now know that we locate our highways in the tropics in beautiful canyons only at our peril. The change of location of this one road will affect the whole countryside, the growth of cities as well as many minor enterprises. For our Philippine highways of the future, in highland country at least, we must resort to the ridges, for on them we are safe, while in the canyons we have overhanging cliffs and powerful undercutting streams to contend with.

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[10] Influence of geographical environment, p. 452.

Landslips

In consequence of the nature of the formations, heavy rainfall, and seismic disturbances, nearly all parts of the archipelago are subject to landslips of greater or less magnitude. This is particularly true of the highlands of Luzon, where in many localities the formations are to a considerable extent limestone covered with volcanic flows and loose ejecta. At one place near Sagada, Lepanto subprovince, the writer saw a piece of terrane on which was located an entire Igorot village of several hundred houses creeping slowly down the mountain side. At Baguio, in the case of another slide, he recorded by actual measurement a slip of an inch an hour. This great slide occurred just below the Government hospital, causing some of the adjacent buildings to be moved, and extended in a great semicircle with an arc of between half and three-quarters of a mile. At the time this visit was made the total settling had amounted to over 30 feet. A landslide from one side of the Bued River canyon during an unprecedented downpour caused a dam of loose material in the gorge below to a height of 60 feet. When the impounded water broke through this dam everything in the canyon below was obliterated for several miles, steel girders of bridges being carried far out onto the Central Plain below, miles to the south.

Location and Growth of Cities

Manila.—The location of Manila is unique not only in the archipelago, but also it is one of the best situated metropolises in the world from geographical, physiographical, and commercial standpoints. In its immediate surroundings the following points of paramount importance are to be noted: It is located about half way between the extreme northern and southern ends of the great island of Luzon, almost at the geographical center. It is at the head of one of the best protected bays in the world. It is at the lower end of the largest of the intermontane areas of the archipelago, the great Central Plain of Luzon. It is at the mouth of the Pasig River, the main artery leading to the rich lake country of the provinces to the southeast. The narrow opening and wide flaring out of the bay on the inside precludes any possibility of serious damage from seismic waves. Although by nature the harbor was not made absolutely typhoon-proof, on account of the size of the bay and low land surrounding most of it, it has been made easily so by building a line of breakwater for a short distance out from the Manila shore. As the greatest single area of agricultural land and the largest easily accessible population is to be found on the Central Plain, Manila is given a commanding trade position within the archipelago. When we consider Manila in its larger world relationship, we see that it is the logical distributing point for a vast and richly productive region. This preeminence is due to its geographical position, about midway between the rich and populous Pekin plain and the valley of the Yangste in China and Australasia, and its situation with respect to the whole of Malaysia—-a world in itself and almost unknown to America—a region which can supply all the tropical products America can use and which is learning to use many of the luxuries produced by the United States. The building of the Panama Canal has brought Manila into even closer relationship with America than was formerly enjoyed, by establishing a more direct connection with the Atlantic States.

Dagupan, Luzon.—This city is located at the head of Lingayan Gulf, once an important entrepot for ships, but no longer so. It still is important as a "mountain gate" city, standing at the upper end of the great Central Plain, and is an important point on the Manila and Dagupan Railroad, for years being the northern terminal of this railway.

Cebu, Visayas.—This, the second city of the archipelago, is the main distributing point in the Visayans and enjoys a good anchorage and shelter from storms.

Iloilo, Visayas.—The third city in size at the present time; but destined to surpass Cebu because it has what the latter has not—a productive back country. It is growing very fast and has good shelter and anchorage. Both Iloilo and Cebu would suffer from waves produced by seaquakes, owing to the funnel-like nature of their harbors.

Zamboanga, Mindanao.—A beautiful little town which is situated on a prominent trade route to Australia. It has little tributary country.

Cotabato, Mindanao.—Slightly off the Australian trade route, but has an immense and potentially rich region to dominate. Some day this should be the metropolis of the southern islands.

Aparri, Luzon.—Owes its measure of prominence to the great Cagayan tobacco country. Its poor harbor facilities and distance from main steamship tracks always will militate against it.

Legaspi, Luzon.—Depot and entrepot for the rich hemp district of southeastern Luzon, this settlement should increase in importance when the railway from Manila reaches it, though it has an unprotected harbor.

Nueva Caceras, Luzon.—Is located at the head of navigation for small ocean-going vessels on the Bicol River. It also taps the Albay hemp region. This town probably never will become of the first importance because none but shallow-draught boats can reach it.

INFLUENCE OF GEOLOGIC ENVIRONMENT ON NATIVES

The Philippine Islands afford some interesting data showing the dependence of people on their geologic environment. This also may throw some light on the question of the duration of the so-called Stone, Iron, and Bronze "ages" of man. From our reading we naturally would gather the impression that these "ages" followed one another in order, and that each was of considerable duration. The last may be true, but the fact that these periods of economic or mechanical processes of civilization may have overlapped to a considerable degree usually has not been properly emphasized. At San Esteban, Ilocos Norte, as shown by Christie,[11] the Ilocanos make stone vessels, mortars, etcetera, though they do not, as far as is known, use stone implements; so that it is not a strictly bona fide "stone age" community. The Igorots of Mancayan, until recently, and perhaps at this very time, smelt their own copper and beat out pots of various sizes. In the Bulacan Mountains the Tagalogs are engaged in making plowshares and points by the thousands in their crude furnaces. In Mindanao the Moro is a brass-worker, it being easier for him to get that than any other metal or alloy. So, by stretching a point, we have all three metals, as well as stone, playing a leading part in the lives of these peoples. The islanders use each and all of them simply because they are at hand, but all are found in the same age. It is reasonable to suppose that the availability of the particular material for use has been the controlling factor in the reason for its employment rather than any varying in the degree of intelligence of the workers; and it is conceivable that some future archeologist might come, with his isolated and insufficient data, to make some generalization which would be wholly unwarranted by the truth.

Even vulcanism, with all of its dire accompaniments, has its compensations, and to it can be traced several unsuspected benefits. Three especially pertinent illustrations may be cited:

The Government engineers have found that the Manila plain, which is almost entirely made up of loose pyroclastics alternating with shaly and clayey beds, is an exceptionally good source of artesian water. Hundreds of these wells have been bored since the American occupation, and the effect for the better on the health of the natives has been truly wonderful. A second benefit is manifested in the fact that, although the outpouring of acid gases and ashes from Taal Volcano in 1911 destroyed the orange crop—the principal industry of that section—for that year, in the succeeding years increased yields were given. Still a third compensation is the great number of hot springs of medicinal and saline waters which furnish the people with remedies and with salt for their food.

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[11] Philippine Journal of Science, vol. vii, no. 4.

Coral Reefs

There are two dominant formations to be found in or about most Pacific islands, in Oceania especially. These are volcanic ejecta and coral, and both are intimately bound up with the life and economy of the peoples inhabiting that part of the world. Some Pacific islands are all volcanic, some all coral, and many are made up of both kinds of formations.

Coral formations are extensive in the Philippines—the Coast and Geodetic charts show to what extent—about 65 per cent of the coast lines of the archipelago having been surveyed.

This subject alone would provide material for a very ample paper or even a book. It is not necessary to go into the subject of the origin of coral reefs, but a few facts about the growth of coral might not be without interest, especially those points relating to the influence of the coral formations on the life of the peoples living near them.

As Becker[12] and others have pointed out, there are several benches or raised coral reefs on some of the Philippine coasts, particularly those of northwest Luzon; and on the island of Cebu it is possible to go from the living reef on the coast inland to nearly 3,000 feet elevation on continuous coral reef formations. Not much can be contributed here about the contact of these reefs with the underlying rock because of the lack of good sections in favorable places and also for the reason that the writer was not looking for this sort of thing when in the neighborhood, being concerned principally with economic questions. However, in a few places the reefs were found to make an unconformable contact with eroded igneous rock beneath. In many parts of the islands the coral grows close to shore, with no gap between—that is, the latter joins snugly onto the former.

As would be expected, the top of coral reefs is a fairly flat platform, the limiting plane being the level of the sea. The outer edge is rather an abrupt slope dipping off into deep water. The surface has more or less numerous holes in it which are filled with water. Opposite the mouths of debouching streams there are, almost without exception, open channels, the current and the influx of fresh water both being deleterious to the coral polyp.

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[12] G. F. Becker: Twenty-first Annual Report, U. S. Geological Survey, 1901.

Some of the direct and indirect benefits derived by the inhabitants from coral or coral-fringed islands are as follows:

a. Coral reefs furnish a platform on which alluvium is deposited, and hence contribute to the lateral extension of the land.

b. The reefs protect the land from marine erosion.

c. They afford a source of lime.

d. They provide building stone.

e. Upraised coral formations yield especially fine transported soils, but not good residual soils.

f. They impound the ground water and thus afford better flows of artesian water from wells bored behind the reefs.

g. They even may afford protection from hostile craft seeking a landing to attack the inhabitants.

h. In many places they afford an easy line of travel along stretches of coast where there are cliffs and no roads inland.

i. In and about the reefs at low tide fishermen find all sorts of shellfish and even ordinary fish in innumerable tidal pools.

j. To a limited degree they furnish a means of livelihood to collectors of coral specimens for museum and curio purposes.

Temperament of the Natives

In the course of the writer's many journeys from island to island and long trips inland he has noted, without being able to explain satisfactorily, the peculiarity of the primitive music of the peoples of the archipelago. It has the same plaintive, almost sad, quality of all Malay and Polynesian music. A musician might explain this more simply and directly, but it has occurred to the writer that this quality is the effect of environment. A people who are continually harassed by typhoons, locusts, earthquakes, plagues, and volcanic eruptions ought to feel sad. Their ignorance of and lack of power to cope with these natural phenomena makes them of a mystical turn of mind. Men usually do not laugh at things they can not understand.

Climate and Sunlight

The temptation to digress for a few lines on the general subject of the influence of tropical climate and tropical sunlight on man, and more particularly on white men, is too strong to be withstood. The writer realizes that these topics are not strictly connected with geology in just the way in which they are taken up, but some discussion of this subject may not improperly be inserted here. It would take too long and be too entirely out of place to go into this topic exhaustively or even to enumerate all the work that has been done along this line. The reader should, if he already has not done so, read the very suggestive work by the late Colonel Woodruff, United States Army: "The Effect of Tropical Sunlight on White Men."

It is the writer's opinion that many of the bad effects attributed to climate and sunlight in the tropics have been exaggerated and have existed largely in the minds of those who have paid more attention to theories than to the actual facts, knowing from nine years' personal experience that no unusual inconvenience was suffered. It is probable that by taking regular exercise one could live throughout the regular working period in the Philippines without any appreciable loss of efficiency.

The Malays never have indulged in athletics to any extent commensurate with our own addiction to sports, but since the now extensive program of athletics for the Filipinos has been promoted by the Government a marked improvement in the physical and mental stamina of the native can be noted, while the changes in diet introduced by the Americans also has had its effect.

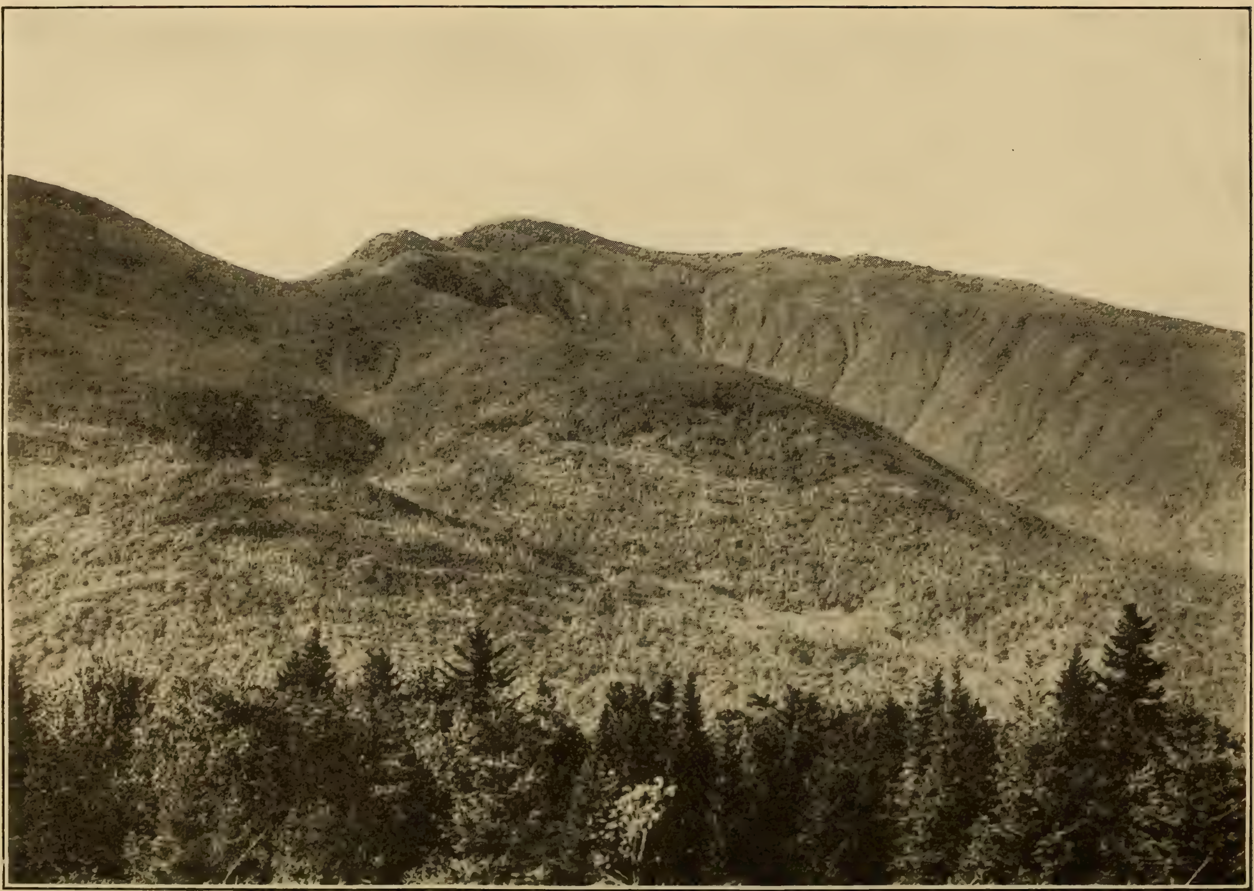
One delusion of the white man has been forever dispelled in the Philippines, namely, that whisky is essential to one's physical well-being in the tropics. If the Englishman seems to have thrived on alcohol in the tropics, it need only be asked how much better he would have thriven, how much greater things would he have done, without it.

Effect of modern Improvements

The railroad, the macadam road, and the telegraph are the powerful factors at work now in breaking up the age-long isolation of the tribes of the Philippines. In time tribal differences will almost disappear, and until they do we can not hope for any political unity of these peoples which will be lasting.

When we look carefully and considerately into the environment of the Filipinos, we find much to explain their backwardness and lack of concerted action. "People who live in regions of ascending air currents, low barometer, high temperature, and excessive rainfall lack initiative and energy." When we take into account the additional handicaps of rugged mountain barriers, tempestuous seas, and plagues of all sorts to contend with, we must give the people of the Philippines due credit for surviving at all.

To the future historian of these peoples the writer ventures to give this bit of advice: Study the topography and geology of the archipelago and that of the Far East, then no one needs be surprised at the rational manner in which events hang together and are mutually explanatory.



VALLEY OF SNYDER BROOK (AT LEFT) AND KING RAVINE (AT RIGHT)

Showing striking contrast due to profound glacial erosion of the latter

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DATE OF LOCAL GLACIATION IN THE WHITE, ADIRONDACK, AND CATSKILL MOUNTAINS[1]

BY DOUGLAS WILSON JOHNSON

(*Read before the Society December 27, 1916*)

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INTRODUCTION

The student of land forms finds in the White Mountains of New Hampshire exceptional opportunities for pleasant and profitable field excursions. To the advantages afforded by Prof. J. W. Goldthwait's excellent descriptions of the salient topographic features of the Presidential Range are added ease of accessibility to all parts of the mountains over trails constructed by the Appalachian Mountain Club, and the existence of an expressive contour map prepared by Mr. Louis F. Cutter.

During a short visit to the region in the summer of 1914 I enjoyed still further advantages through the courtesy of Prof. W. O. Crosby, who not only provided excursions to different parts of the range in his automobile, but also joined me on tramping trips over the highest peaks for the purpose of discussing in the field points open to debate. Let me here record my indebtedness for many valuable suggestions received in the course of these discussions.

THE PROBLEM STATED

According to Goldthwait's descriptions, the Presidential Range represents a complex mountainous mass, which was first reduced by normal

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[1] Manuscript received by the Secretary of the Society May 4, 1917.

processes to a late mature stage of erosion; later uplifted to permit a marked incision of stream valleys in the flanks of the subdued range; and finally modified by a local glaciation which was sufficiently intense to develop excellent cirques, but which was not continued long enough to consume all the preglacial upland or to produce sharp alpine peaks. The accuracy of these essential elements of Goldthwait's interpretation will scarcely be questioned by the physiographer. The remarkable contrast (plate 36) between the normal valley of Snyder Brook, with its sloping sides and overlapping spurs, and the deep-cut amphitheater of King Ravine, bounded by rocky walls descending precipitously to a broadly open floor, can only be explained by assuming that both valleys were originally of similar form, but that King Ravine alone suffered strong modification by a local glacier. Others of the White Mountain "ravines" and "gulfs" are unquestionable glacial cirques of more or less typical form, and in association with unconsumed remnants of preglacial upland recall the submature glacial features of the Big Horn Mountains in Wyoming. Tributary valleys such as Jefferson Ravine (plate 37, figure 1) and Tuckerman Ravine enter the main valleys with the distinctly discordant junctions characteristic of a local glacier system, while few places in the country afford more typical glacial troughs than those of the Great Gulf and Crawford Notch (plate 37, figure 2).

When one considers the more detailed features of White Mountain physiography, it appears that certain hypotheses advanced by Goldthwait to explain topographic peculiarities of the range merit further study. His suggestion that the cirques were completed by local glacial erosion *before* the coming of the continental ice-sheet is novel, while his interpretation of the well known felsenmeer on the higher summits as a local block moraine deposited by the continental glacier is not in accord with the usual explanation of this feature. One may question, also, his correlation of the White Mountain "lawns," small remnants of a graded upland near the mountain tops, with the so-called Cretaceous peneplane of southern New England (plate 37, figure 2). It is the first point alone that I would direct attention in the present paper.

EVIDENCE DERIVED FROM THE WHITE MOUNTAIN CIRQUES

Among the considerations which led Goldthwait to assign an early date to cirque cutting in the White Mountains, two deserve special mention. In the first place, there is a noticeable absence of important local moraines at the mouths of the cirques. In Goldthwait's opinion the scooping out of the great mass of rock necessary to transform a preglacial valley into

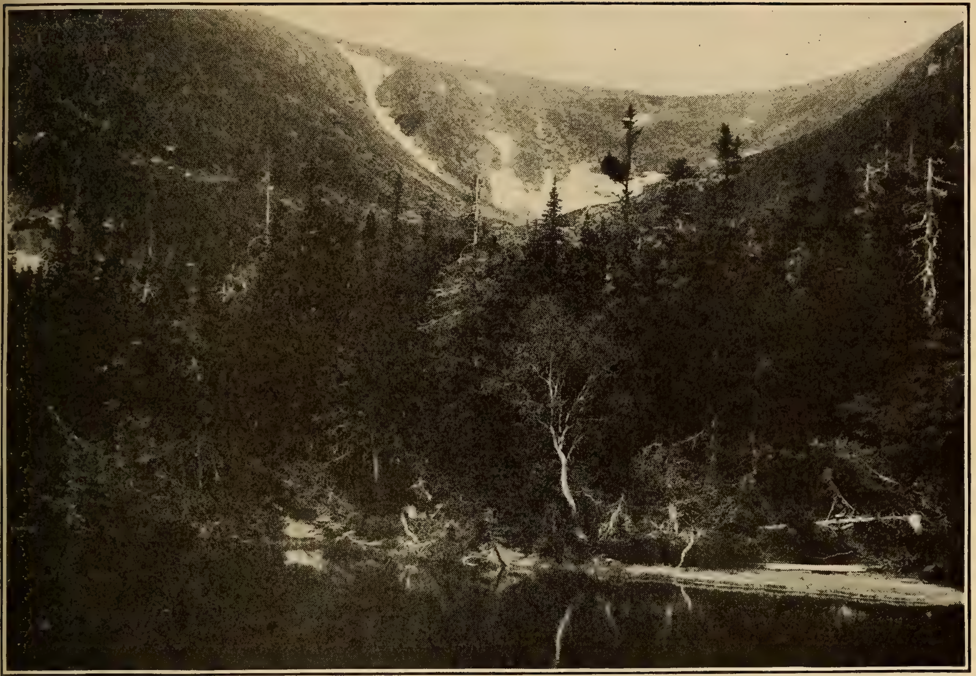


FIGURE 1.—JEFFERSON RAVINE, A HANGING GLACIAL CIRQUE

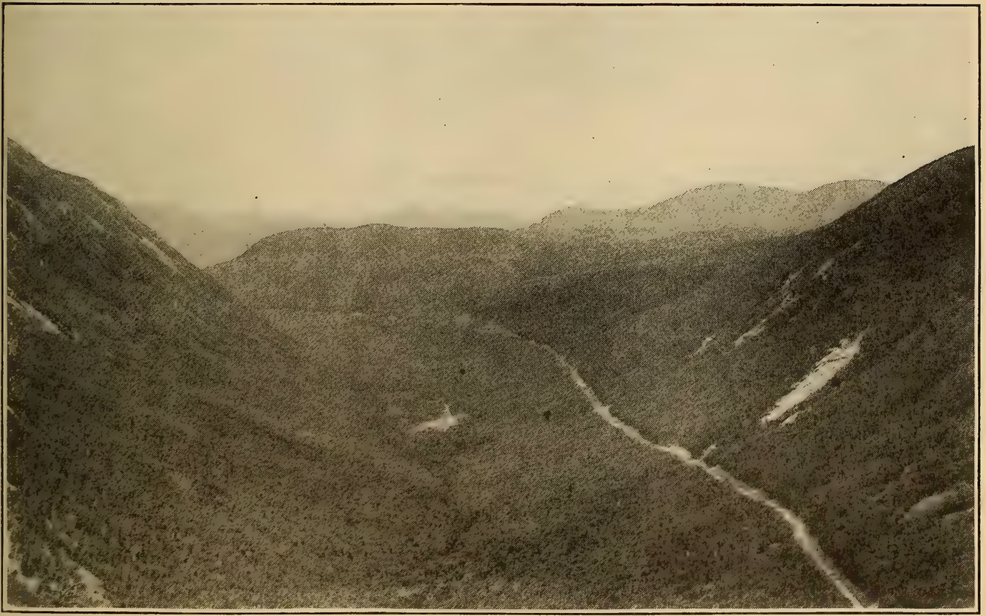


FIGURE 2.—CRAWFORD NOTCH, A VERY SYMMETRICAL GLACIAL TROUGH

The bench in the middle distance is probably to be correlated with the so-called Cretaceous peneplane, above which the main peaks of the White Mountains rise as monadnocks

TYPES OF GLACIAL TOPOGRAPHY IN THE WHITE MOUNTAINS

the present King Ravine cirque "must have been accompanied by the depositing somewhere at or beyond the mouth of King Ravine of a great terminal moraine of equal proportions. There can be only one explanation for the absence of the local moraine . . . these valleys were ice carved *before* and *not after* the great ice-sheet swept across New England, and only those records of local alpine glaciers remain which the ice-sheet did not obliterate" (1913(*a*); 11). In further support of this interpretation, it is pointed out that the headwalls of cirques opening toward the northwest are less precipitous and less ragged than are those of cirques opening to the southeast, a contrast which should be expected if the southeastward-moving continental ice-sheet impinged against the headwalls of northwest-facing cirques and rubbed them down, at the same time passing over or plucking blocks from the heads of those facing southeast. For the same reason, Great Gulf, which lay athwart the path of the continental glacier, has a steep northwest side-wall and a more gently sloping wall on its southeast side (1913(*a*), 12; 1914, 461).

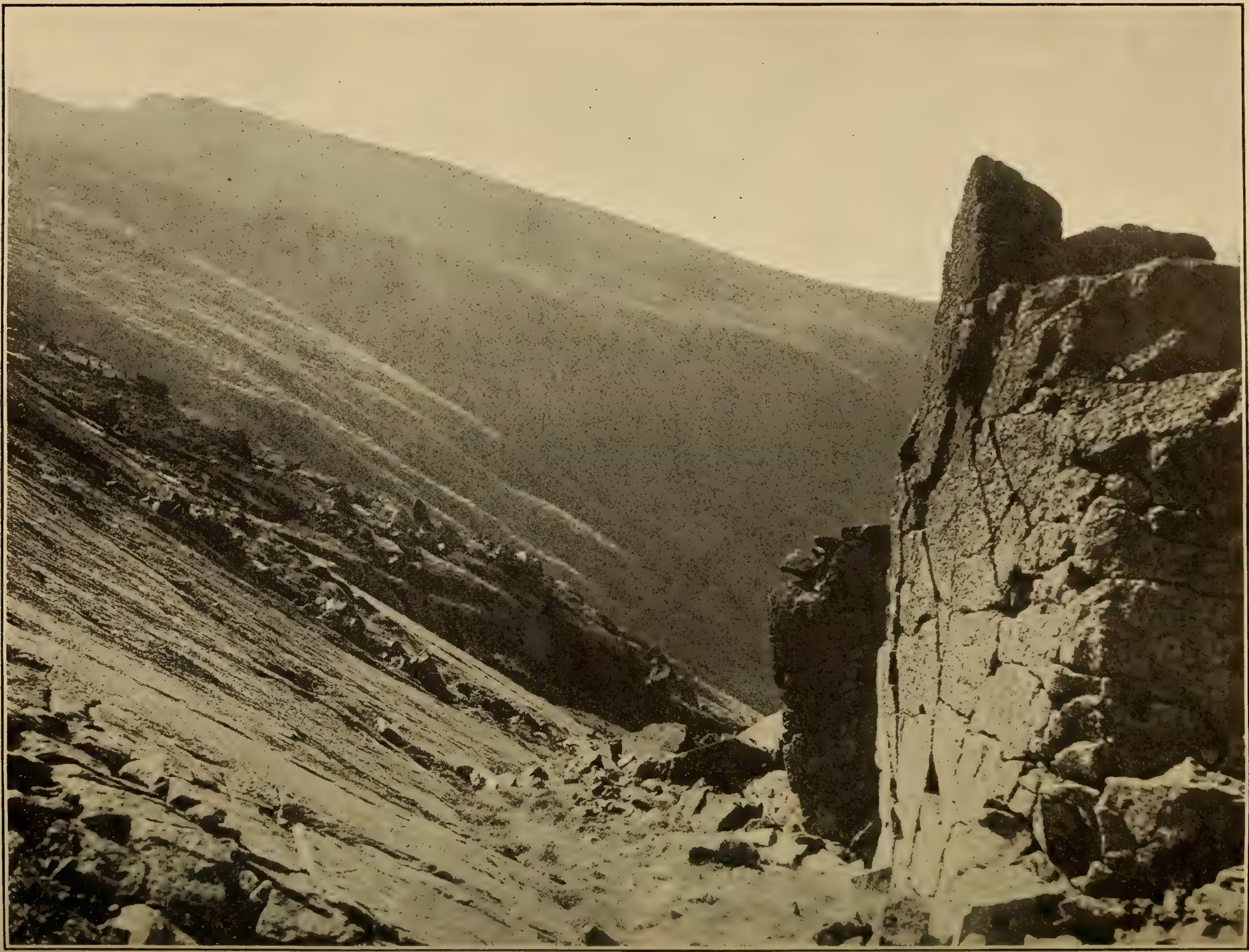
It does not appear that the supposed early date for the cirques receives much support from the arguments quoted above. It is the writer's impression that moraines proportional in size to the amount of material eroded are seldom found at the mouths of cirques or troughs. Certainly it is more usual to find but a fraction of the eroded material deposited in the form of a terminal moraine. During the thousands of years that the cirque is being carved streams from the melting ice are constantly carrying away much of the erosion product, sometimes to deposit it as a valley train or outwash plain, sometimes to transport it to more distant regions. Indeed, theoretical considerations are not opposed to the hypothesis that in many cases the amount of glacially eroded debris removed by stream action might be so great that no significant morainal ridges would be formed. The field experience of glacial students confirms this hypothesis, for more than one has commented on the marked disparity in volume between certain large cirques or troughs and their associated small moraines. Prof. E. de Martonne, for example, informs me that in the Carpathian Mountains, where no question of continental glaciation complicates the problem, large moraines are surprisingly rare. Out of ten glacial cirques, on an average not more than one or two would have moraines of appreciable size, while the majority would have no true moraines associated with them. The absence of important moraines opposite the mouths of White Mountain cirques, therefore, does not justify the conclusion that such moraines were once formed, but were later removed by the continental ice-sheet.

Where mountain ranges are being uncovered by a waning continental ice-sheet, conditions may be peculiarly favorable for the erosion of cirques without the formation of important moraines. After the surface of the continental ice has been lowered some distance down the flanks of a range, local glacial systems develop in the upper levels of the mountain valleys and carry on the work of cirque-cutting. Such cirques are of later date than the continental glaciation of the levels at which they develop; but so long as the continental ice is moving past the lower flanks of the range the material eroded from the cirques may be carried down to it by the local glacier system, and hence be transported entirely out of the region in the body of the main ice-sheet.

It seems highly probable that the conditions just described obtained in the White Mountain region during the waning of the Wisconsin ice-sheet. If so, then only the insignificant amount of debris removed during the very last stages of cirque-cutting could in any case have been left opposite the ravine mouths.

The contrast in slope of headwall which exists between northwest- and southeast-facing cirques is occasionally very striking; but there is some evidence that this variation in form is related in part to structural planes in the rocks composing the range, and in part to conditions affecting the alimentation of the local glaciers, rather than to the modification of early cirques by the continental ice-sheet. Parts of the Presidential Range are intersected by strongly marked joint planes dipping in a general northerly or northwesterly direction. Headwalls of cirques facing in the direction of dip will tend to coincide with the major structural planes; for even if cirque-cutting originally leaves a headwall vertical, rock slides along the planes of weakness must soon reduce the wall to a more gentle slope. Where the joint planes dip into the headwall, this tendency, of course, does not exist. King Ravine, facing slightly west of north, shows very clearly the coincidence of much of its sloping headwall with major joint planes (plate 38). It is into the bowl of this cirque that the most important rock slides have been precipitated (plate 39, figure 1), and Goldthwait has himself emphasized the importance of the sloping joint planes in contributing to the development of the slides.

The gently sloping southeast wall of the Great Gulf may similarly be related to structural features. Although the crystallines of this region are much disturbed, prominent foliation planes inclined toward the north were noted at a number of places along the carriage road to the summit of Mount Washington and on the slopes of Chandler Ridge. Near the Half-way House they seem to determine the strong contrast in slopes of a small ridge, about which the road makes one of its sharp bends. The



HEAD WALL OF KING RAVINE, WHITE MOUNTAINS

Showing coincidence of surface slope with inclined joint planes

gentle slope of Great Gulf's southeastern wall is not confined to the higher levels, where alone the impact of southeast-moving ice would be effective, but continues unchanged to the depths of the Gulf, as is expectable if structural features have controlled the slope. It is worthy of note, also, that the east wall of King Ravine and the south wall of Tuckerman's Ravine, both exposed to the supposed impact of southeast-moving ice, have not been "rubbed down," but on the contrary are exceptionally sharp and steep.

It is well known that cirques on the eastern side of a north-south mountain ridge are apt to be more strongly developed than those on the west, since a number of factors favor the better alimentation of glaciers on the eastern side. In the Presidential Range the Ravine of the Cascades and the Ravine of the Castles, opening toward the northwest, are on the west side of the main crest, while all the cirques opening toward the southeast are east of the crest. Headward erosion of the latter cirques should be the most effective and produce the steepest headwalls.

Goldthwait's belief in the early age of the cirques does not rest alone on the arguments criticized above; hence any complete discussion of his theory must consider other lines of reasoning which I have not had the opportunity of testing in the field. My object has been not to disprove the theory, but to question the validity of certain arguments presented in its support, and so to keep the minds of other students of the region alive to the possibility that the greater part of the cirque-cutting may, after all, have been accomplished after the continental ice had disappeared from the higher peaks.

DATE OF CIRQUE-CUTTING IN THE ADIRONDACK MOUNTAINS

In support of this latter interpretation one may appeal with some confidence to certain physiographic features in the Adirondack and Catskill Mountains. If local glaciation antedated the coming of the continental ice-sheet in the White Mountains, one should expect the same sequence of events in neighboring mountain regions. If the absence of local moraines in the White Mountains is due to their removal by a later advance of the continental ice, such moraines should, for the same reason, be absent in the Adirondacks and Catskills. On the other hand, if undoubted moraines of local glaciers exist in the two mountain groups last named, this fact would cast serious doubt on Goldthwait's theory of an early date for the local glaciation in the White Mountains. To test this line of reasoning in the field I made brief visits to portions of the Adirondack and Catskill Mountains in the fall of 1916.

More than one geologist has reported evidences of local glaciation from the higher levels of the Adirondacks. Kemp in particular has referred in many of his papers to glacial cirques cut in the sides of different peaks, while Ogilvie briefly describes local moraines "which appear from the character of the drift to have been deposited by glaciers radiating from the center of the Adirondack highlands after the melting of the main body of the ice" (1902, 406). Inasmuch as such descriptions have been for the most part very brief, and have been based on observations made incidental to other geological work, and were, moreover, published before Goldthwait's theory of an early date for the local glaciation had been offered, it seemed desirable critically to examine one or more good examples of the supposed cirques and local moraines with the new point of view in mind. Through the courtesy of Mr. Harold L. Alling, who contributed to our excursions the use of his automobile and his extended knowledge of Adirondack geology, I had the opportunity of making a brief examination of this kind.

It is scarcely probable that any physiographer who has seen the higher ranges of the Adirondack group will doubt the former existence there of local glaciers. It is true that the cirques are poorly developed, and that they are not to be compared with the far more striking examples found in the Presidential Range. Many of them might better be styled "incipient cirques." Nevertheless they betray the characteristic effects of local ice action. A few miles west of Elizabethtown, looking south from the main road to Keene Valley, one sees three broadly open amphitheaters separated by imperfectly developed arêtes, cut in the northeast side of a mountain ridge. Noonmark Mountain, as seen from Keene Valley, exhibits an incipient cirque in its northern slope. Giant Mountain, viewed from Saint Huberts, shows traces of probable local ice action and is scarred by slides presumably due to the oversteepened headwall resulting from incipient cirque-cutting. On Mount Whiteface, one of the highest peaks in the range, the evidence of local ice action is more apparent. Kemp laid special emphasis on the significance of the "amphitheaters or cirques on the slopes of Whiteface" (1898, 62-63). Plate 39, figure 2, reproducing a photograph taken by the writer from the summit of the peak looking north, shows the asymmetry of crest line characteristic of Alpine ridges and exposes the headwall of a cirque cut in the eastern slope.

From the form of the incipient cirques in the Adirondack Mountains it might be difficult to determine whether the local glaciation which produced them occurred before or after the continental ice-sheet buried the range; but the evidence of the moraines should be less equivocal. On

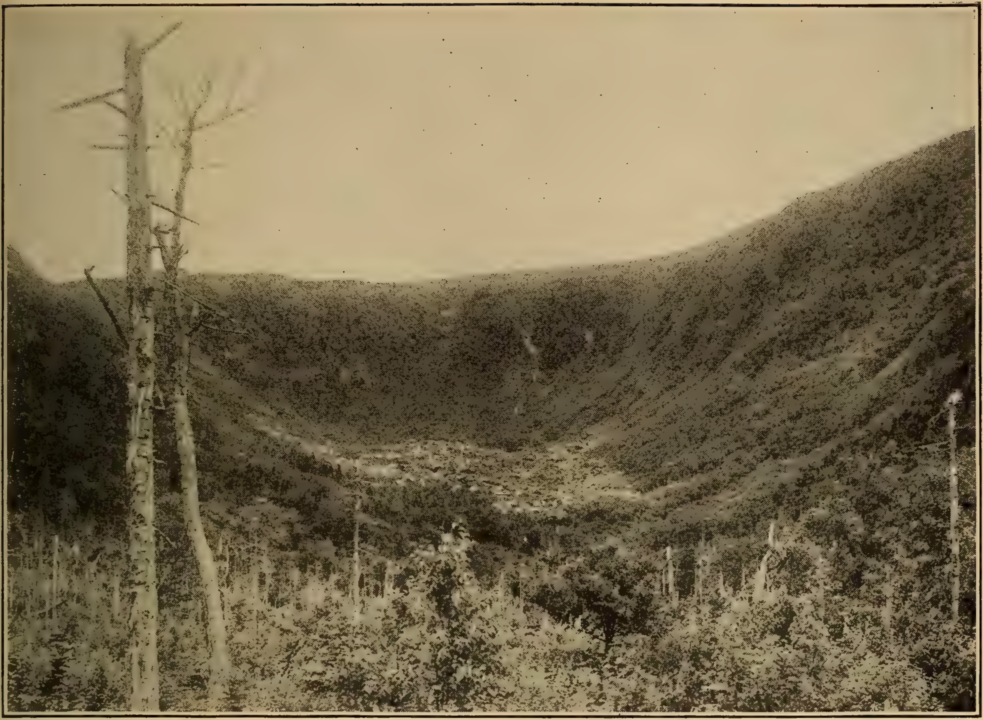


FIGURE 1.—INTERIOR OF KING RAVINE, WHITE MOUNTAINS
Showing rock slide in bowl of cirque

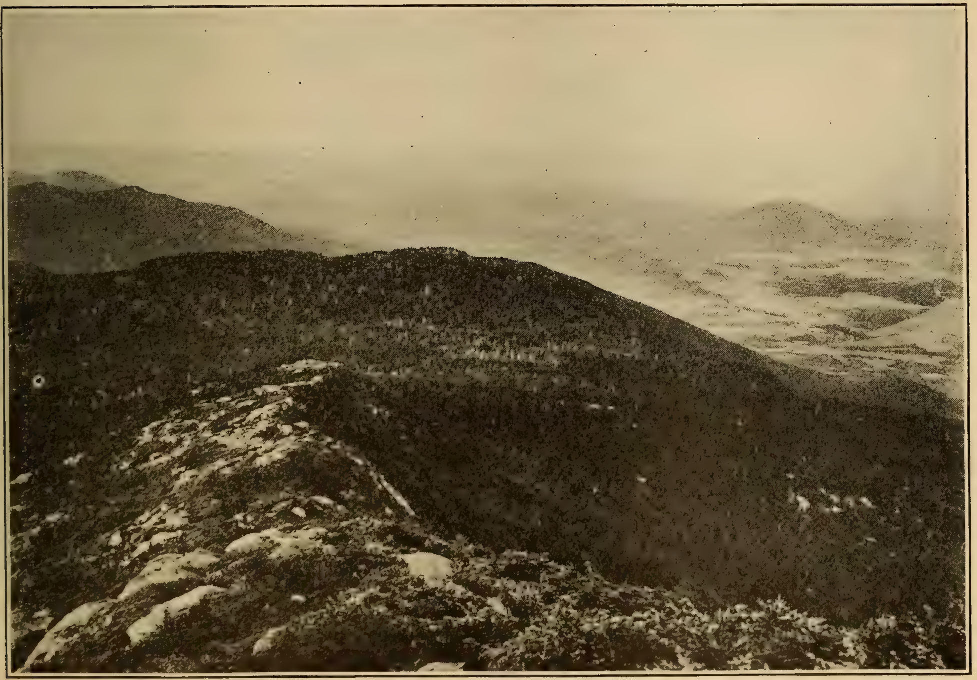


FIGURE 2.—HEAD OF CIRQUE ON MOUNT WHITEFACE, IN THE ADIRONDACKS

CIRQUES OF LOCAL GLACIERS IN THE WHITE AND ADIRONDACK MOUNTAINS

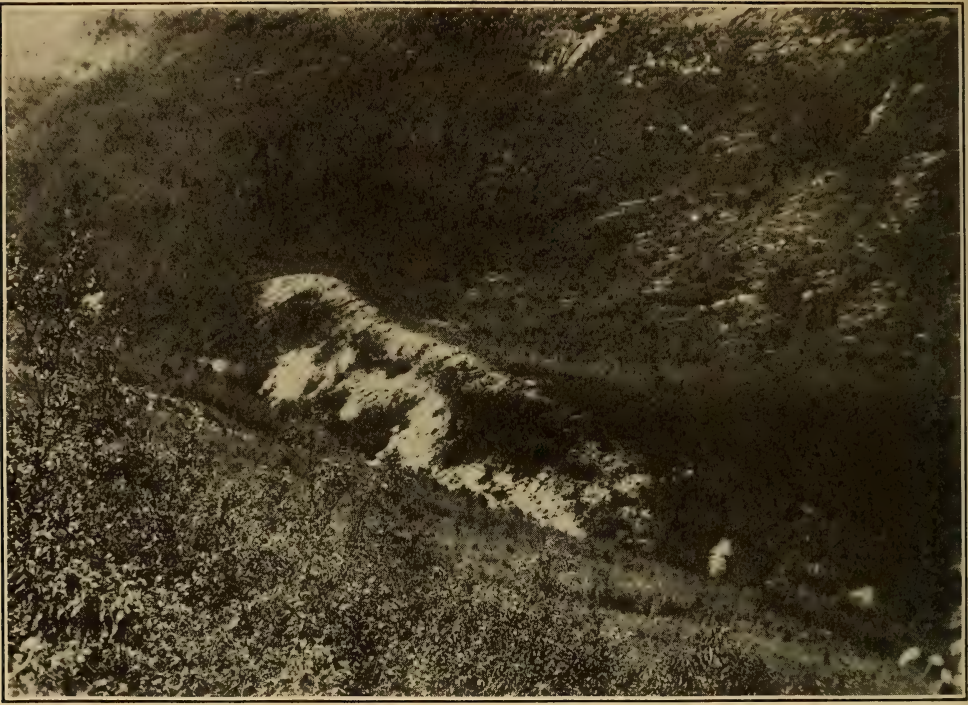


FIGURE 1.—LATERAL MORAINE OF LOCAL GLACIER ON THE NORTHERN SIDE OF MOUNT WHITEFACE, IN THE ADIRONDACKS

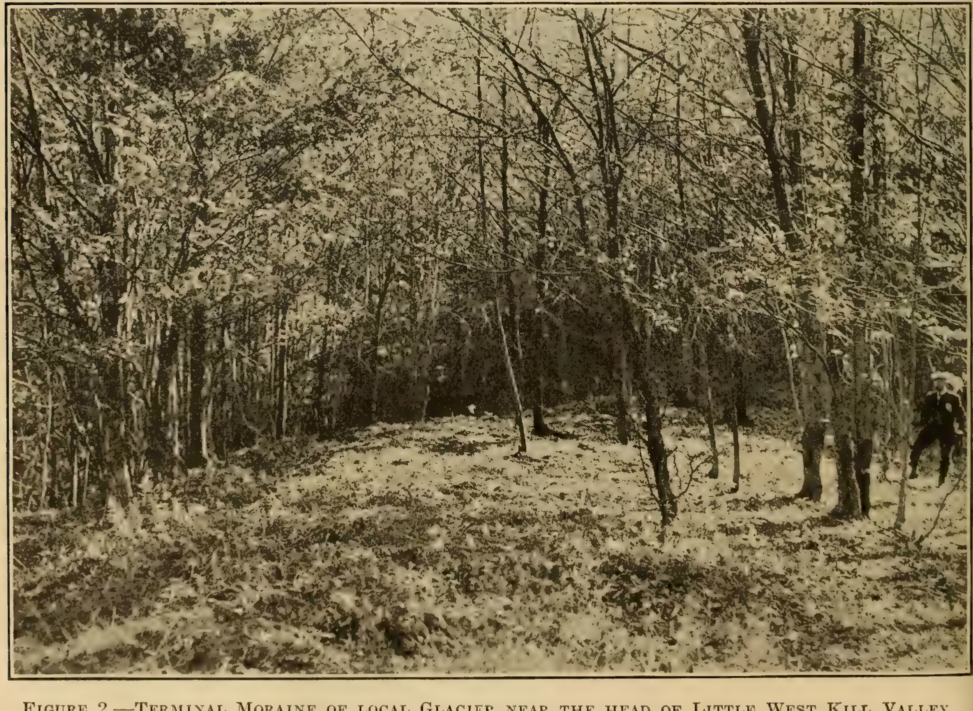


FIGURE 2.—TERMINAL MORAINE OF LOCAL GLACIER NEAR THE HEAD OF LITTLE WEST KILL VALLEY, CATSKILL MOUNTAINS

LOCAL MORAINES IN THE ADIRONDACK AND CATSKILL MOUNTAINS this point we may take as a test case the features which characterize one of the valleys cut on the northern flanks of Whiteface. This valley lies just east of Esther Mountain, and as it faces northward it was exposed to the full impact of the southward-moving continental ice. In form the valley approaches that of a glacial trough, while its headward portion suggests incipient cirque-cutting. On the floor of the trough is a narrow ridge of debris (plate 40, figure 1), about three-quarters of a mile in length. Its form is that of a glacial moraine, not that of a landslide ridge or rock glacier. The fact that it declines distinctly down valley toward the north shows that it was deposited by a northward-moving local glacier, not by a southward-moving tongue of the main ice-sheet. It is scarcely conceivable that this delicate ridge of loose debris could have retained its form if overridden by the continental ice. We must conclude that the local glacier which deposited the moraine existed after the continental ice had disappeared from the region.

Date of Cirque-cutting in the Catskill Mountains

Evidences of local glaciation in the Catskill Mountains have been presented by Rich (1906; 1915), who quotes Chamberlin and Smock as having earlier suggested the probability of such action. The phenomena reported by Rich were so remarkable, especially when one considers the more southerly position of the Catskills as compared with the Adirondacks and White Mountains and the low altitude (about 2,000 feet) at which the local glaciation was supposed to have occurred, that no little doubt attached to his conclusions. I was therefore glad of an opportunity to join Prof. C. P. Berkey on a visit to the localities described by Rich, and particularly glad to have as our companion Professor de Martonne, whose glacial studies in the Alps and Carpathians made his critical judgment of peculiar value in so problematical a case.

We directed our attention especially to two localities near the heads of Little West Kill and Fly Brook valleys respectively. The writer's experience in other portions of the Appalachian Plateau province led him to suspect the danger of landslides from the heads of normal stream amphitheaters cut back in the horizontal sandstones and shales of the Catskill region; and the fact that slides and rock glaciers sometimes simulate morainic topography was kept in mind. A casual inspection of the hillsides about the Little West Kill Valley showed that the slopes were suffering to an extraordinary degree from creeping and slumping (plate 41, figures 1 and 2), and that special care must be exercised to discriminate between slide topography and true moraine. The former presence of the continental ice in the region necessitated further caution to avoid mistaking features formed by tongues of the main ice-body for evidences of local glaciation. I have placed unusual emphasis on these precautionary measures because I want to use conclusions reached in the Catskill study as arguments against the theory of an early date for cirque-cutting in the White Mountains, and it is manifest that the value of the initial conclusions in this case depend on the care exercised by the observer in the field.

In the opinion of the writer some of the evidences of local glaciation cited by Rich are open to doubt. This opinion is subject to the criticism that it was based on a brief reconnaissance and not on any systematic study such as Rich has given to the region. I believe, however, that further investigation will show that some of the supposed morainic accumulations are in part at least of landslide origin. Occasionally what look like landslip scars may be observed above the hummocky accumulations on the valley floor. Some true glacial deposits ascribed to local glaciation seem to me readily explicable as the product of local tongues of continental ice moving *up* the valleys. In the lower valley of Fly Brook are rock ledges showing striæ which have been ascribed to local glaciers. Some of these striæ incline upward at an angle of 30 degrees with the horizontal on the down-valley sides of the ledges, while the up-valley sides of the same ledges show no striæ or only faint ones. Both de Martonne and the writer are inclined to regard this as an indication of ice moving *up the valley,* basing opinion on the expectable behavior of ice when riding up over an obstruction in its channel and on analogy with similar phenomena observed in the Alps where the direction of ice movement is not subject to doubt. We observed nothing which seemed to indicate a movement of local ice for any appreciable distance down valley.

On the other hand, after eliminating all doubtful cases, there remains abundant evidence to substantiate the principal contention of Rich, namely, that local glaciers formerly existed in the Catskill Mountains. Near the head of Little West Kill Valley are a number of ridges which might conceivably have been produced by some form of landslide action. But one of these ridges, after continuing down valley for some distance, curves through an arc of 90 degrees and meets the valley wall abruptly at a right angle. It has the form (plate 40, figure 2) and position of a true moraine. In Fly Brook Valley are two open ravines or amphitheaters, each containing typical crescentic terminal moraines convex down valley. In one valley the moraine (plate 42, figure 1) is neatly trenched by a postglacial stream notch; in the other a beautiful moraine

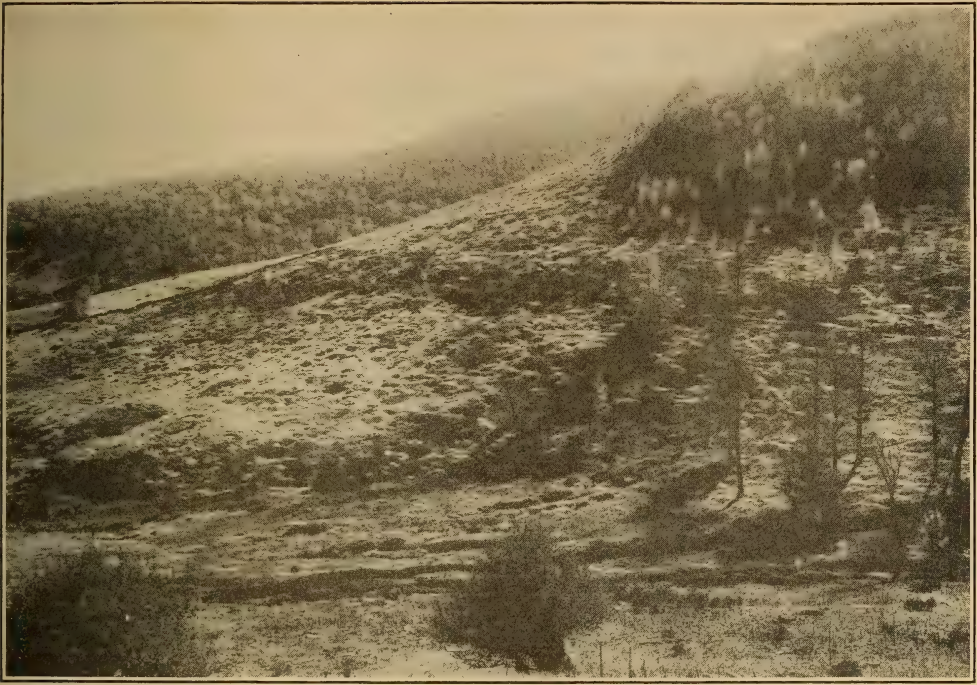


FIGURE 1.—GENERAL VIEW OF PITTED SLOPES DUE TO SURFACE CREEP OF SOIL AND ROCK

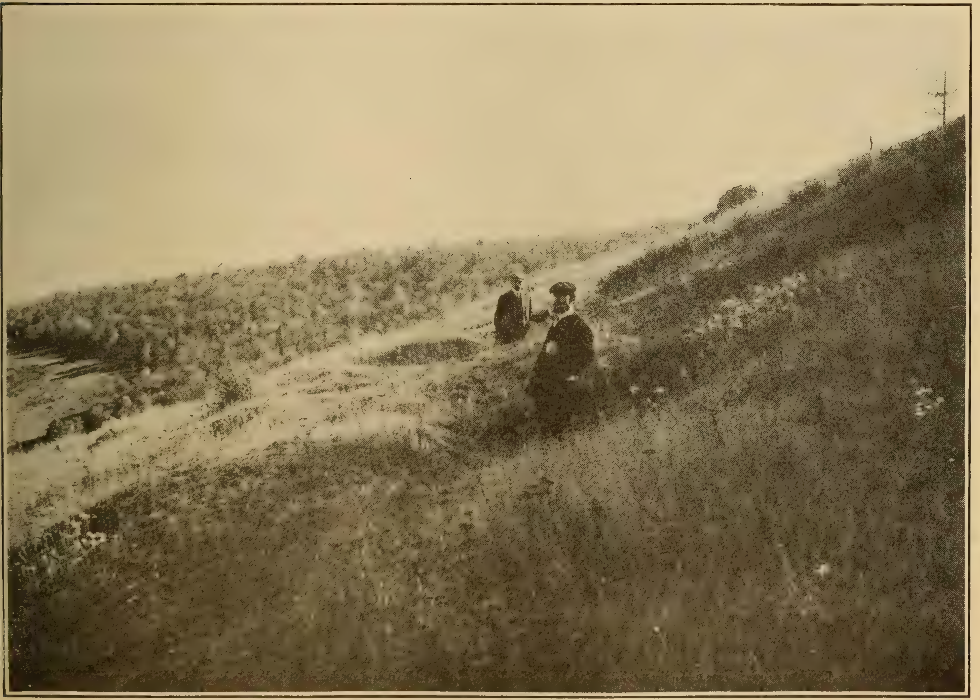


FIGURE 2.—DETAILED VIEW SHOWING SIZE OF PITS

TOPOGRAPHY AT HEAD OF LITTLE WEST KILL VALLEY, CATSKILL MOUNTAINS

This topography is due to extensive soil creep and rock sliding

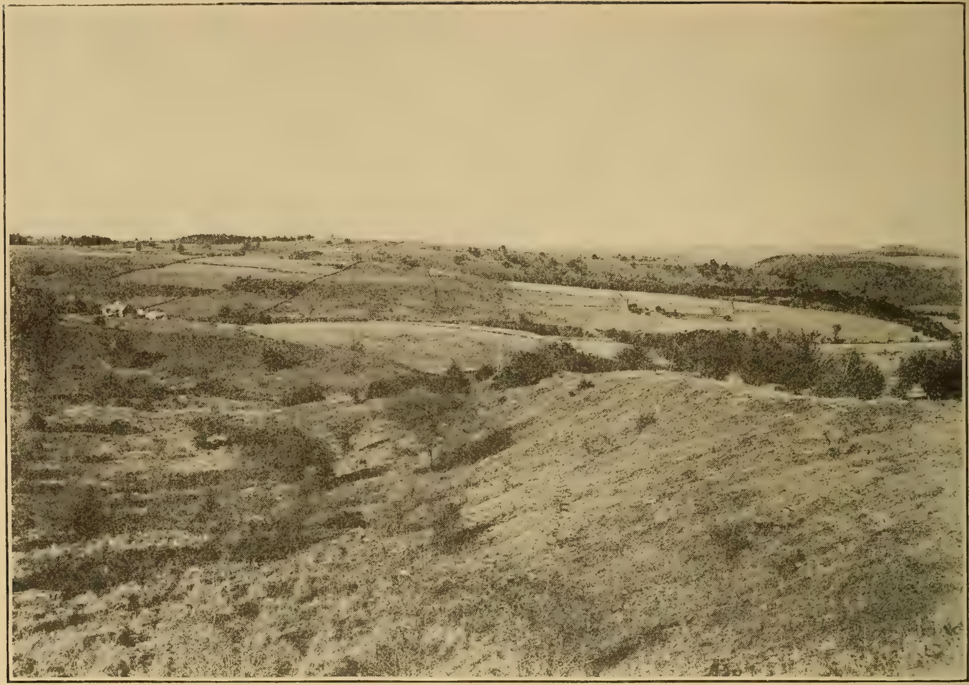


FIGURE 1.—CRESCENTIC TERMINAL MORAINE TRENCHED BY STREAM

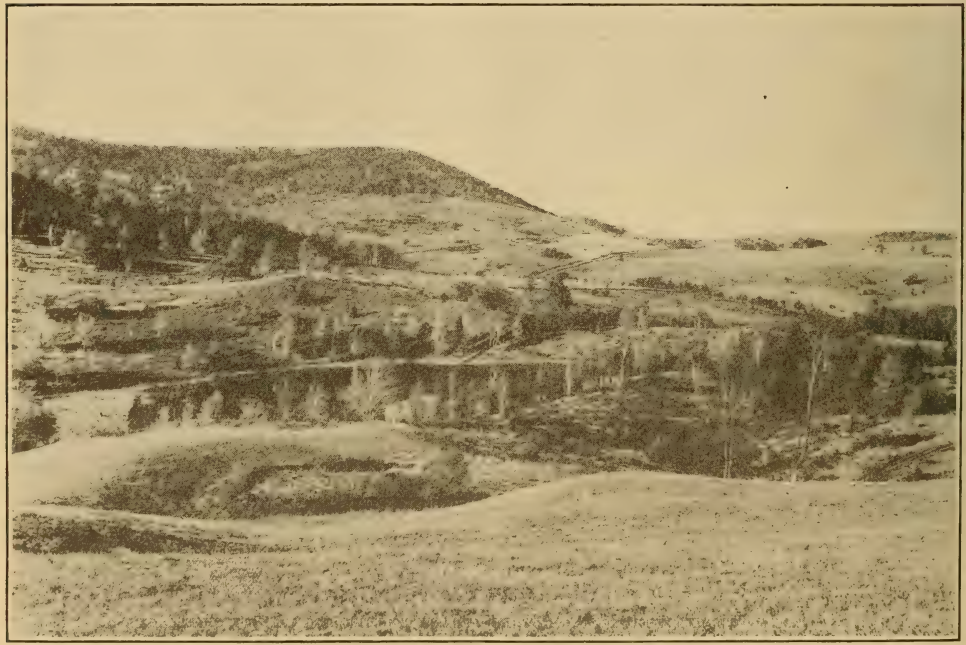


FIGURE 2.—CRESCENTIC TERMINAL MORAINE INCLOSING MORAINE LAKE
Knob and kettle topography in foreground

TERMINAL MORAINES OF LOCAL GLACIERS IN FLY BROOK VALLEY, CATSKILL MOUNTAINS lake (plate 42, figure 2) is held in by a very perfect moraine dam, showing good knob and kettle topography. It does not seem possible to regard these ridges as the product of any agency but ice. It is equally impossible to regard them as deposits from tongues of the continental glacier moving up valley. Their position seems clearly to negative the suggestion that ice spilling across cols at the valley heads might account for their existence. The only reasonable interpretation seems to be the one already offered by Rich; they are terminal moraines of true local glaciers. In the writer's opinion these glaciers were very small and probably very short lived. The moraines may mark their maximum extension down valley. Good cirque topography is lacking, and the bulk of the morainic debris may have slumped down from the valley head without the aid of any appreciable cirque-cutting by the incipient glacier.

The date of local glaciation in the Catskills seems scarcely open to question. No moraines could preserve the delicate features characteristic of the Fly Brook and Little West Kill ridges had they been overridden by the continental ice. There can be little doubt that the Wisconsin ice covered the low altitudes at which the moraines occur when the ice-front lay in the latitude of Long Island. Later fluctuations of the ice-margin may have failed to reach the localities in question; but that local glaciation occurred subsequent to the main advance and retreat of the Wisconsin ice seems assured.

CONCLUSION

To the criticisms urged against certain of the arguments advanced in support of an early date for local glaciation in the White Mountains we have added evidence that the new theory can not successfully be applied in the Adirondacks and Catskills. Tarr's description (1900) of lateral, medial, and terminal moraines of local glaciers on Mount Ktaadn indicate that equal difficulty may be encountered in attempting to apply the theory in the mountains of Maine. These considerations justify further study of White Mountain physiography before Goldthwait's theory is accepted for that region.

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VOL. 28, PP. 553-602 SEPTEMBER 30, 1917

REVISION OF THE STRUCTURAL CLASSIFICATION OF PETROLEUM AND NATURAL GAS FIELDS *

BY FREDERICK G. CLAPP

(Presented before the Society December 28, 1916)

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Introduction

When we consider the variety of different conditions prevailing in oil fields, it is evident that some sort of a classification is needed. In order to be of most practical service, this should be based on the most conspicuous distinguishing factors prevailing in a majority of the fields. What, then, is the most conspicuous type of phenomena displayed in an undeveloped oil field? Without doubt, it is the geological structure; hence we choose structure as the starting point in our classification, as we do in our detailed field investigations.

The structural factor has been realized for several decades by the exponents of the anticlinal theory, and in 1910[1] the structural classification was proposed as an offshoot of that theory. The purpose of this paper is to broaden the subject by discussing, first, the classification, and secondly the apparent exceptions. We might almost say that the knowledge of favorable structures is approaching a stage where the exceptions will be more important than the rule; but, nevertheless, the structural rules themselves remain the predominant guide in any field investigation.

In revising the classification, it is a pleasure to give credit for a number of additions to Bosworth,[2] Johnson and Huntley,[3] Mrazek,[4] and others. The writer also is indebted to the McGraw-Hill Book Company, to the United States Geological Survey, and to Economic Geology for permission to make copies of certain cuts republished here.

REVIEW OF THE ANTICLINAL THEORY

In considerations of geological structure much has been heard in the past about the "anticlinal theory," which has been of decided value in locating many oil and gas fields. That theory was first suggested by Hunt[5] and was later investigated and advocated by Andrews,[6] Winchell,[7] Stevenson,[8] Minshall,[9] Newberry,[10] Hofer,[11] and others. The theory was not definitely formulated, however, until 1885, when Doctor White[12] worked out its details and first applied the theory in practice by locating oil and gas fields in West Virginia and Pennsylvania by means of it.

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[1] A proposed classification of petroleum and natural gas fields based on structure. Read before the Geological Society of Washington March 9, 1910. Abstract, Science, vol. 31, no. 801, May 6, 1910, pp. 718-719. Published in full in Econ. Geol., vol. 5, no. 6, Sept., 1910, pp. 503-521.

The use of geological science in the petroleum and natural gas business. Proc. Engrs. Soc. W. Pa., vol. 26, no. 4, May, 1910, pp. 87-120. Read before that Society April 19, 1910.

[2] T. O. Bosworth: Outlines of oil-field geology. Pet. Review, March-April, 1912, pp. 139-140, 171-172, 203-204, 235-236.

[3] Principles of oil and gas production, 1916, pp. 63-66.

[4] R. L. Mrazek: Congress International du Petrole, 1907.

[5] T. Sterry Hunt: Notes on the history of petroleum or rock oil. Can. Nat., vol. 6, August, 1861, pp. 241-255; Can. Geol. Survey, 17th Rept. of Progress, 1863-1866, p. 233.

[6] E. Benjamin Andrews: Rock oil, its geologic relations and distribution. Am. Jour. Sci., 2d ser., vol. 32, 1861, pp. 85-93.

[7] Alexander Winchell: On the oil formation in Michigan and elsewhere. Am. Jour. Sci., 2d ser., vol. 39, 1865, p. 352.

[8] J. J. Stevenson: Sec. Geol. Survey of Pa., vol. H, 1875, pp. 394-395.

[9] F. W. Minshall: In letters to the State Journal, Parkersburg, W. Va., in 1881.

[10] J. S. Newberry: Geol. Survey Ohio, vol. 1, 1873, p. 160.

[11] Hans Höfer: Das Erdol und seine Verwandten, 3d edition, p. 166; Geologie des Erdols, p. 18.

[12] I. C. White: Sci., vol. 6, June 26, 1885; Bull. Geol. Soc. Am., vol. 3, 1892, pp. 187-216; W. Va. Geol. Survey, vol. 1-A, 1904. pp. 48-64.

Doctor White's theory was applied strictly to saturated rocks. Orton[13] deserves great credit for deciphering the detailed structure of structural terraces along similar lines of research. The various theories for the accumulation of oil have been ably summarized by Campbell.[14] In fact, the anticlinal theory has been advocated by so eminent authorities as to be apparently accepted for many years.

Limitations of the anticlinal Theory

In practice, however, the anticlinal theory frequently has not met expectations. After making careful locations of wells based on this theory, operators sometimes were rewarded only by dry holes. The successes, overshadowed by the fancied failure of the theory, were lost sight of by practical oil men, and thus the theory fell largely into disrepute for a time. The reports of the United States Geological Survey and the various State geological surveys throughout the country contained references to the anticlinal theory, and every writer on the subject tried to show the geological relation of fields in the particular territory covered. In many cases the geologists were successful in finding some relation, and in most instances the major axes of pools were discovered to correspond in a general way with the main anticlinal and synclinal axes. Many pools correspond closely with the crests of anticlines and seemed to prove the theory. Other cases prevail, however, in which the relation was less striking, and some exist in which no relation could be determined.

To explain the apparent defects of the theory various so-called "limitations" were formulated. The limitations, like the original theory, were incomplete in their application. They, too, have been added to and reviewed by various geologists, until now little seems to be left of the original "anticlinal theory." Great advances have been made, however, consequent on detailed mapping of geological structure by Government surveys and private geologists. While we have not yet reached, and may never reach, the knowledge by which a production can be infallibly located, we may truthfully assert that geology can now save a large proportion of dry holes, as well as bonuses and rentals on prospective oil territory.

Statement of the structural Theory

The improvement in the value of geology to oil development was largely due to the evolution of the "structural theory." This term seems preferable to "anticlinal theory," in order to explain definitely the relations which accumulations of oil and gas hold to geology within certain limitations, even where no definite anticline or syncline exists. The structural theory, as understood by the writer of this paper, is as follows:

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[13] Edward Orton: Geol. Survey Ohio, vol. 6, 1886, pp. 21 and 94.

[14] M. R. Campbell: Historical review of theories advanced by American geologists to account for the origin and accumulation of oil. Econ. Geol., vol. 6, no. 4, 1911, pp. 362-386.

Through some means, by organic or inorganic agency or agencies, the petroleum and gas have come into or been generated in the porous formations in which they are found. The deposits may have originated through the decomposition of plant or animal remains on an ancient sea-bottom, as the adherents of the organic theory claim; or, they may be the product of chemical action deep in the earth, as the adherents of the inorganic theory claim; or, certain petroleum deposits may be of organic and certain other deposits of inorganic origin. Whichever theory is true, the oil, gas, and water in the formations (assumed to have been approximately horizontal at the time the substances entered them) were at first widely diffused in the porous formations or contiguous strata. They have remained in their diffused condition to the present time in many parts of the world, where only small quantities of oil and gas, too slight for profitable development, have been found, and where the dip of the rocks is very slight.

Where the beds have been folded, however, as in the greater part of the Appalachian region and in most oil fields throughout the world, the oil, gas, and salt water have been enabled to separate out according to their relative specific gravities. This separation and concentration may have been assisted by rock pressure, diastrophism, hydraulic pressure, seepage, capillarity, molecular attraction, internal heat, and other causes; but whatever causes prevailed for the movement of the oil, gas, and water, the law of gravitation, being ever operative, must be considered of most importance in determining their arrangement; hence the accumulation was in the order of the densities of the substances.

The structural theory agrees with the anticlinal theory, of which it is an outgrowth, in acknowledging that on a stated anticlinal, monoclinal, or quaquaversal structure gas lies nearest the top, oil lower down, and still lower is the salt water, when present. Whether the pools occur at the top of the anticlines, lower on their slopes, or in the synclines, is determined by factors of secondary importance.

History of the structural Classification

What is known as the "structural theory" or structural classification is a natural outgrowth of the "anticlinal theory." The structural classification was first proposed by the present writer in a paper before the

Geological Society of Washington on March 9, 1910,[15] and published in September of that year.[16] While adequate to include most producing oil and gas structures known at the time, it manifestly needed further explanation and subdivision; so that on December 29, 1910, a paper on certain aspects of monoclinal accumulation was presented before the Geological Society of America in Pittsburgh, Pennsylvania, and published in January, 1911,[17] previous to which time monoclinal pools had been supposed to exist chiefly in terraces. This paper was followed in June, 1912, by one on quaquaversal or dome structures.[18] A few facts were added in 1913[19] and a few additional facts in 1916.[20]

In 1915 a classification of seepages or oil springs was proposed by De Golyer[21] as follows:

I. Seepages associated with igneous intrusions.
   (*a*) At contact zones of volcanic plugs and sedimentary rocks.
   (*b*) At contact zones of dikes and sedimentary rocks.
   (*c*) Through cracks and fissures in the igneous rock itself.
   (*d*) As intrusions in the igneous rock.
   (*e*) From metamorphosed rock above an intrusion which does not outcrop.

II. Seepages not associated with intrusions.
   (*a*) At crest of domes or anticlines.
   (*b*) Along marked fault or fissure planes.
   (*c*) From steeply dipping strata.
   (*d*) Isolated occurrences of uncertain relations.

The classification of seepages did not modify the classification of structures, but furnished several ideas for its further subdivision, and is mentioned here on account of its general bearing on the subject. Since little criticism has been made of the structural classification as proposed by the present writer, which appears to have been quite generally accepted, it now seems time to bring it into final form, which is done herewith. The subdivision has been carried still further and several new classes added, in accordance with suggestions received from time to time.

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[15] Science, n. s., vol. 31, no. 801, May 6, 1910, pp. 718-719.

[16] A proposed classification of petroleum and natural gas fields based on structure. Econ. Geol., vol. v, no. 6, pp. 503-521.

[17] Notes on the occurrence of oil and gas accumulation in formations having monoclinal dips. Econ. Geol., vol. vi, no. i, 1911, pp. 1-12.

[18] The occurrence of oil and gas deposits associated with quaquaversal structure. Econ. Geol., vol. vii, no. 4, 1912, pp. 364-381.

[19] Outline of the geology of natural gas in the United States. Econ. Geol., vol. viii, no. 6, 1913, pp. 517-542.

[20] In a special chapter by F. G. Clapp: Bacon and Hamor's "Principles of oil and gas production," vol. 1, 1916, pp. 34-68.

[21] E. De Golyer: Econ. Geol., vol. 10, 1915, p. 654.

POPULAR MISCONCEPTIONS OF THE STRUCTURAL THEORY

In presenting this classification it is necessary to repeat the note of warning that favorable structures do not hold oil in every case. The idea that every anticline or dome holds oil is as frequent and erroneous as is the impression that all coal is of Carboniferous age, and as petroleum geologists we must do our best to correct it.

We must also remember that an anticline is rarely symmetrical, and that in all asymmetrical anticlines one flank is more favorable than is the other or the exact crest. We must realize that unconformities exist, and that even in the absence of unconformities strata are seldom parallel; also that deformation in itself may suffice to prevent an axis from standing vertical. We must take full account of known and possible water conditions, differences in porosity, etcetera. In short, we must acknowledge that favorable structures are so numerous and complicated that predictions based on them must be made with the greatest care, taking into account not only the structure itself, but all other geological and physical phenomena involved. It is our duty, not only to ourselves but to our clients, to make as fine distinction as possible and not to leave any person with an idea that the solution in a new and unknown field is a simple one.

THE STRUCTURAL CLASSIFICATION

FORMULATION OF THE CLASSIFICATION

The object of the classification is to describe the various types of accumulations by grouping them into classes, each division of which follows a special rule of structure and all of which have certain aspects in common. The classification, as elaborated to date, is as follows:

Classification of Oil and Gas Structures

I. Aclinal or subaclinal structure.
II. Anticlinal and synclinal structures.
  (*a*) Strong anticlines standing alone.
  (*b*) Well defined alternating anticlines and synclines.
  (*c*) Broad geanticlinal folds.
  (*d*) Overturned folds.
  (*e*) Lenticular nature of the sands.
III. Monoclinal structure.
  (*a*) Monoclinal noses.
  (*b*) Monoclinal ravines.
  (*c*) Structural terraces or "arrested anticlines."
  (*d*) Lenticular nature of the sands.
IV. Quaquaversal structures, or "domes."
  (*a*) Anticlinal bulges or "cross-anticlines."

- (b) Monoclinal bulges.
- (c) Closed saline domes.
- (d) Quaquaversal structure caused by volcanic plugs.
- (e) Perforated saline domes.

V. Contact of sedimentary and igneous rocks.
- (a) Contact of sedimentaries with volcanic plugs.
- (b) Contact of sedimentaries with dikes.
- (c) Contact of sedimentaries with intrusive beds.
- (d) Contact of sedimentaries with other igneous rocks.

VI. Strata dipping unconformably away from an old shoreline.

VII. Crevices of igneous rocks.

VIII. Crevices of sedimentary rocks.

IX. Faults.
- (a) Upthrow side.
- (b) Downthrow side.
- (c) Overthrusts.

X. Sealed in by bituminous deposits.

CLASS I—FIELDS IN ACLINAL OR SUBACLINAL STRUCTURE

The term acline is defined by Webster's Dictionary as "Without inclination; horizontal." It differs from "acclinal," which means leaning on another stratum. True aclinal formations are rare in geology. Therefore, though proposed by Johnson and Huntley as a part of a summarized classification, it does not need consideration here, except to explain that the main cause of oil and gas accumulations is some sort of inclination and folding. Where these do not prevail the oil, gas, and water remain in their original unassorted state, and we have no pool of commercial value. A corollary to this principal has been observed in many localities where the sands are nearly, though not absolutely, flat, and a large number of wells get traces of oil and gas, while little in quantity exists at any particular point.

Properly speaking, we may define subaclinal beds as those approximately flat, sometimes not dipping over 10 to 20 feet per mile, too slight a dip to fully separate the oil and gas from the accompanying water. Occurrences of gas or oil in such regions are generally mere showings, encouraging to a prospector, but seldom resulting in real production. The Electra pool in Texas is, however, mentioned by Johnson and Huntley as an example of aclinal structure, the maximum dip being only 15 feet per mile.

CLASS II—FIELDS ASSOCIATED WITH ANTICLINAL AND SYNCLINAL STRUCTURES

General discussion.—This is the class of oil accumulation with which we are most familiar. It is generally supposed to predominate in a majority of oil fields of the world, and as a matter of fact is common in the Appalachian, Ohio, Indiana, Illinois, Mid-Continent, Wyoming, northern Louisiana, and some of the California fields in this country, and supposedly in the Russian, Austrian, Burma, and Borneo fields in the eastern hemisphere. Class II is divided into five subclasses, in order to distinguish between various structural relations in which oil is found associated with anticlines and synclines.

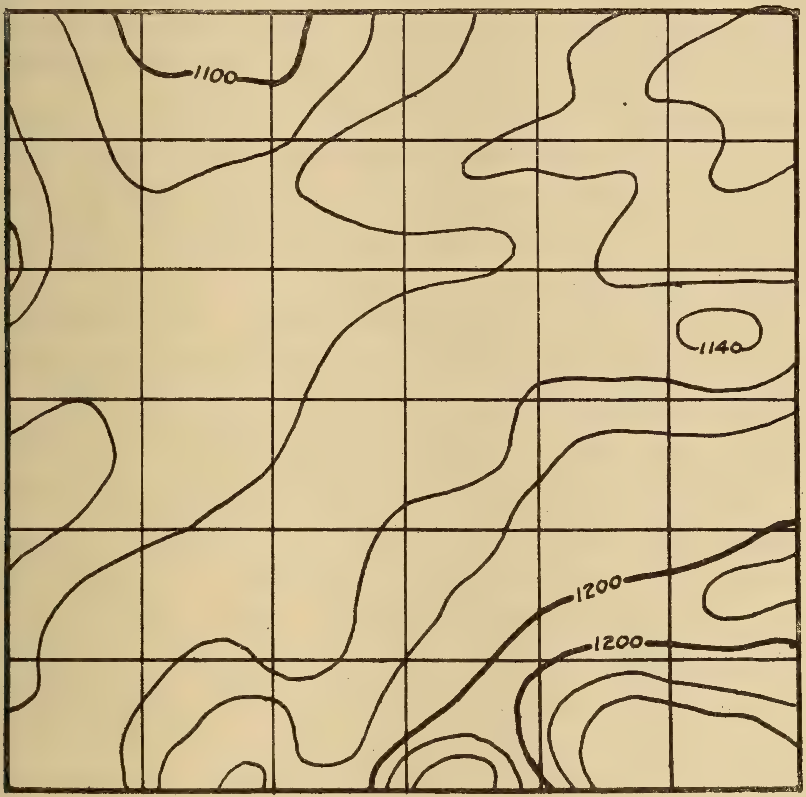

FIGURE 1.—*Example of subaclinal Structure (Class I) in Stephens County, Oklahoma*
Scale: 1 inch = 1.45 mile; contour interval, 20 feet

The best known examples of the distinctions in Classes II and III come from Ohio, West Virginia, and Pennsylvania, where some of the largest oil and gas fields exist. A generalized cross-section of these fields from west to east is shown in figure 2. In this section the pools of Subclass II(*c*) are situated on the crest of the Cincinnati geanticline in northwestern Ohio and northeastern Indiana, the oil and gas being contained in the Trenton limestone. The pools of Class III are on the broad monoclinal dip of over 200 miles extending across central and eastern Ohio, in which the oil and gas occur mainly in the Clinton and Berea sands. Near the Pennsylvania boundary line the dip becomes stronger and more variable, changing the monoclinal dip laterally into definite anticlines and synclines, and it is in these structures that pools of Subclass II(*b*) exist. Anticlinal and synclinal structures are more and more prominent eastward, until in near central Pennsylvania and in central West Virginia metamorphism appears to have been sufficient to drive out all important accumulations of oil or gas, which, although they presumably once existed, escaped to the surface and disappeared long ago.

Symmetrical anticlines.—A good example of a symmetrical anticline is, according to Thompson,[22] the Yenangyuang oil field of Burma, which has yielded the main oil supply in that country from sands of Lower Neocene age, where dome structure is well displayed. The Bibi-Eibat field of Russia is mentioned by the same writer as another symmetrical anticline, modified by doming and faulting.

Asymmetrical anticlines.—Asymmetrical anticlines are, however, most prevalent in oil fields, examples of these being the Grosny field of Russia, the Yenangyat field of Burma, and the Campina field of Roumania. A cross-section of the Grosny field is given by Kalitsky,[23] of the Yenangyat field by Pascoe,[24] and of the Campina field by Mrazek.[25] Many of the fields of Galicia are of this nature, a good instance being the Boryslav-Tustanowice field, which is the principal field of that country.[26]

Subclass II(a)—Where strong anticlines exist standing alone.—In this division are included fields that bear a direct relation to *very pronounced* uplifts, easily recognizable, and constituting a marked geologic feature of the region. The only prominent example in the eastern fields of the United States is the Volcano anticline in West Virginia. This anticline is 25 miles in length, ranging in trend from north 10° west to north 20° east, from an eighth of a mile to half a mile broad on its flat crest, and has side dips of from 20 to 60 degrees. The anticline differs somewhat in direction from the main Appalachian folds and was probably produced by a different set of forces. It is one of the earliest recognized anticlines in the country, having had a great number of wells drilled on it, and has

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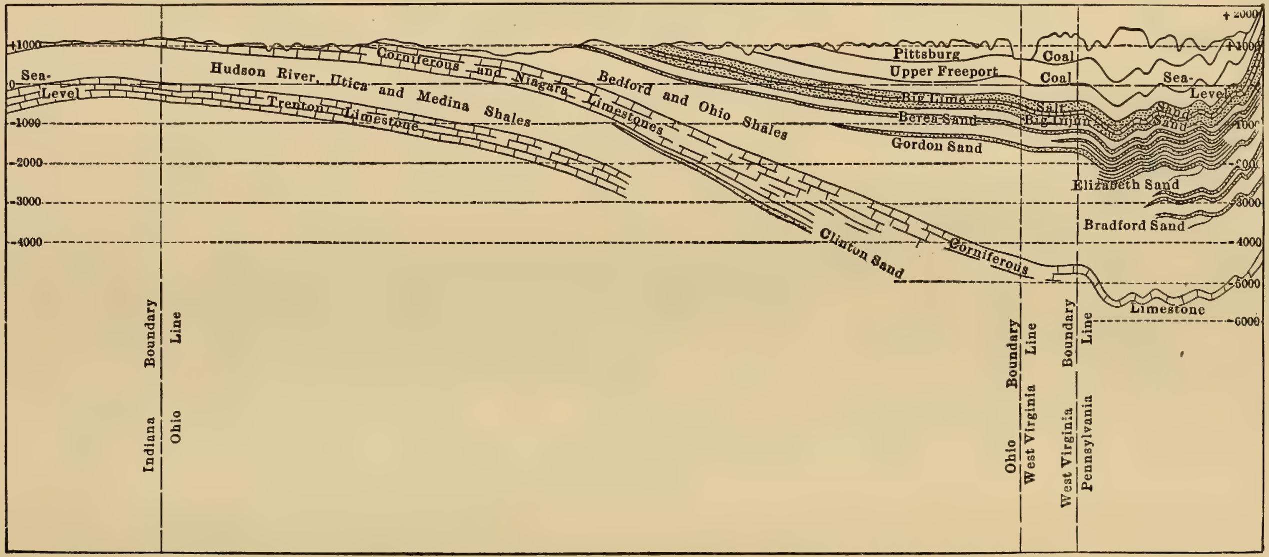
[22] A. Beeby Thompson: Trans. Instn. of Min. and Met., vol. 20, 1910-1911, p. 219 (1911).

[23] K. Kalitsky: Mem. Geol. Com., St. Petersburg, no. 24, 1906.

[24] E. H. Pascoe: Records Geol. Survey India, vol. 34, 1906.

[25] R. L. Mrazek: Congress International du Petrole, 1907.

[26] J. Grybowski: Bull. Acad. Sci., Cracow, 1907.


+1000
Sea-
0 Level
-1000
-2000
-3000
-4000
Indiana Boundary
Ohio Line
Hudson River, Utica and Medina Shales
Trenton Limestone
Corniferous and Niagara Limestones
Bedford and Ohio Shales
Clinton Sand
Corniferous
Pittsburg
Upper Freeport
Big Lime
Berea Sand
Gordon Sand
Ohio Boundary
West Virginia Line
West Virginia Boundary
Pennsylvania Line
Coal
Coal
Salt
Big Injun
Sand
Sand
Sea-
Level
Elizabeth Sand
Bradford Sand
Limestone
+2000
+1000
1000
2000
3000
4000
5000
6000

· FIGURE 2.—*Generalized Cross-section from Cincinnati Anticline to Allegheny Mountains*

Showing relative positions and geological structure of the various Ohio and Pennsylvania fields

Scale: Horizontal, 50 miles = 1 inch; vertical, 5,000 feet = 1 inch

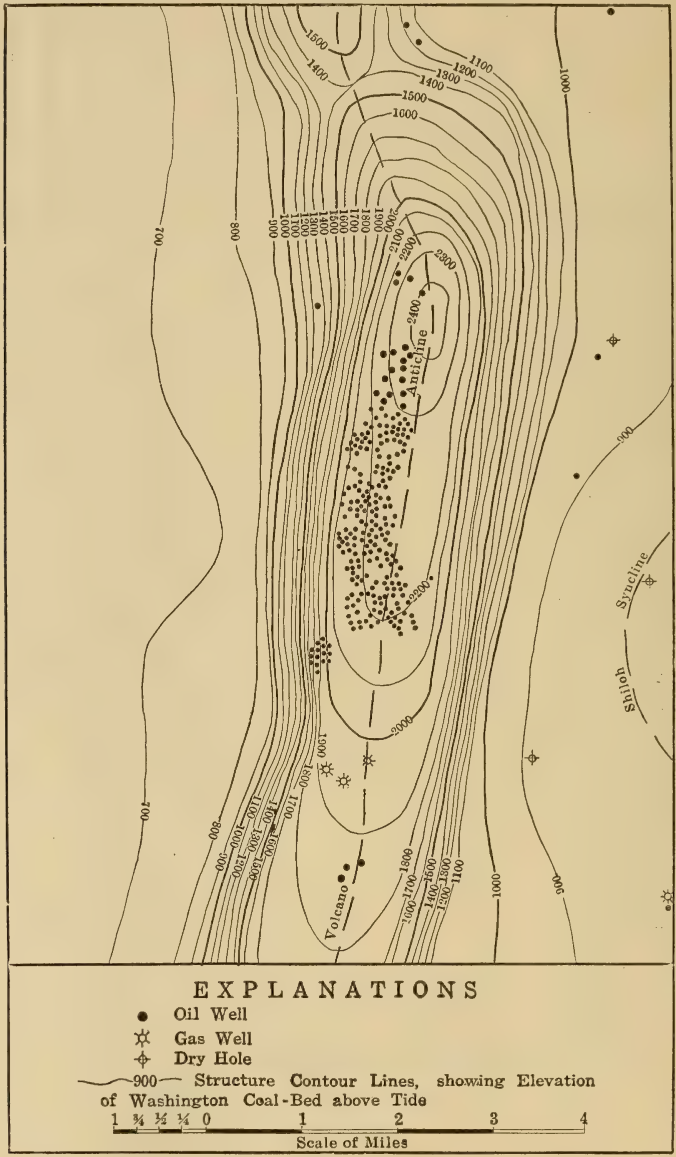

Anticline
Volcano
Syncline
Shiloh
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
EXPLANATIONS
● Oil Well
☼ Gas Well
⌖ Dry Hole
—900— Structure Contour Lines, showing Elevation of Washington Coal-Bed above Tide
1 ¾ ½ ¼ 0 1 2 3 4
Scale of Miles

FIGURE 3.—*Geological Structure of a Portion of the Volcano Anticline in Wood, Ritchie, Wirt, and Pleasants Counties, West Virginia*

Showing type of fields of Subclass II (*a*), bounded on both sides by unproductive subaclinal structure of Class I. Contour interval, 100 feet. (After I. C. White, G. P. Grimsley, and Roy V. Hennen: County reports and maps of Pleasants, Wood, and Ritchie counties, West Virginia Geological Survey, 1910.)

been described by White,[27] Andrews,[28] and Evans.* A map of a typical portion of it is shown in figure 3. The pools of the La Salle anticline in Illinois and some of the California fields belong to this class, as does at least one field in Oklahoma and several in Texas.

Subclass II(b)—Where well defined alternating anticlines and synclines exist.—This may be considered as a composite of Subclass II(*a*). With minor exceptions, it includes the pools of the Appalachian field in Pennsylvania and West Virginia, some in southern Indiana and Illinois, certain Oklahoma fields, the Caddo field of Louisiana, and certain fields in Wyoming. The anticlinal crests in this subclass range all the way from 2 or 3 miles apart, as in Trinidad, to the great geosyncline of the Ohio Valley, which is at least 200 miles across.

The strata in the fields of Subclass II(*b*) are folded into alternating anticlines and synclines having dips seldom more than 30 degrees from the horizontal. This is the subclass to which the anticlinal theory was originally applied. It is illustrated in figure 4, where the sand is or has been wet; but the oil field occupies the syncline, where the sands are practically dry in a region.

The Caddo field has geologically nothing in common with the Spindletop, Humble, Jennings, and other fields in the Coastal Plain of Louisiana and Texas, but it has certain similarities in structure with the fields of Pennsylvania, West Virginia, and Illinois. In northern Louisiana the great oil-accumulating structure is the Sabine uplift, and the local distribution of oil and gas is due to minor anticlines and synclines, accompanied by differences in porosity of the Upper Cretaceous formations which exist there.

Several of the California oil fields also belong in this class, namely, the Coalinga field and the Los Angeles field, according to descriptions by Eldridge[29] and by Arnold and Anderson.[30] The Baku and Surakhany fields of Russia and the Yenangyuang field in Burma appear to come in this subclass. The Negritos and Lobitos fields in Peru are reported to lie on the eastern flanks of an extensive series of anticlinal structures, the axis of which is almost parallel to the Pacific Ocean.

Subclass II(c)—Broad geanticlinal folds.—This is an extreme type of II(*a*). By a geanticline is meant an anticline which is extremely long and broad and constitutes more than a local feature, extending over thousands or tens of thousands of square miles. One of the best examples

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[27] I. C. White: Bull. Geol. Soc. Am., vol. 10, 1899, p. 29.
[28] E. B. Andrews: Am. Jour. Sci., 2d ser., vol. 32, 1861, pp. 85-93.
* E. W. Evans: Am. Jour. Sci., 2d ser., vol. 32, 1866, pp. 334-343.
[29] Geo. H. Eldridge: Bull. 213, U. S. Geol. Survey, 1902, pp. 306-321.
[30] Ralph Arnold and Robert Anderson: Bull. 357, U. S. Geol. Survey, 1908, pp. 70-71.

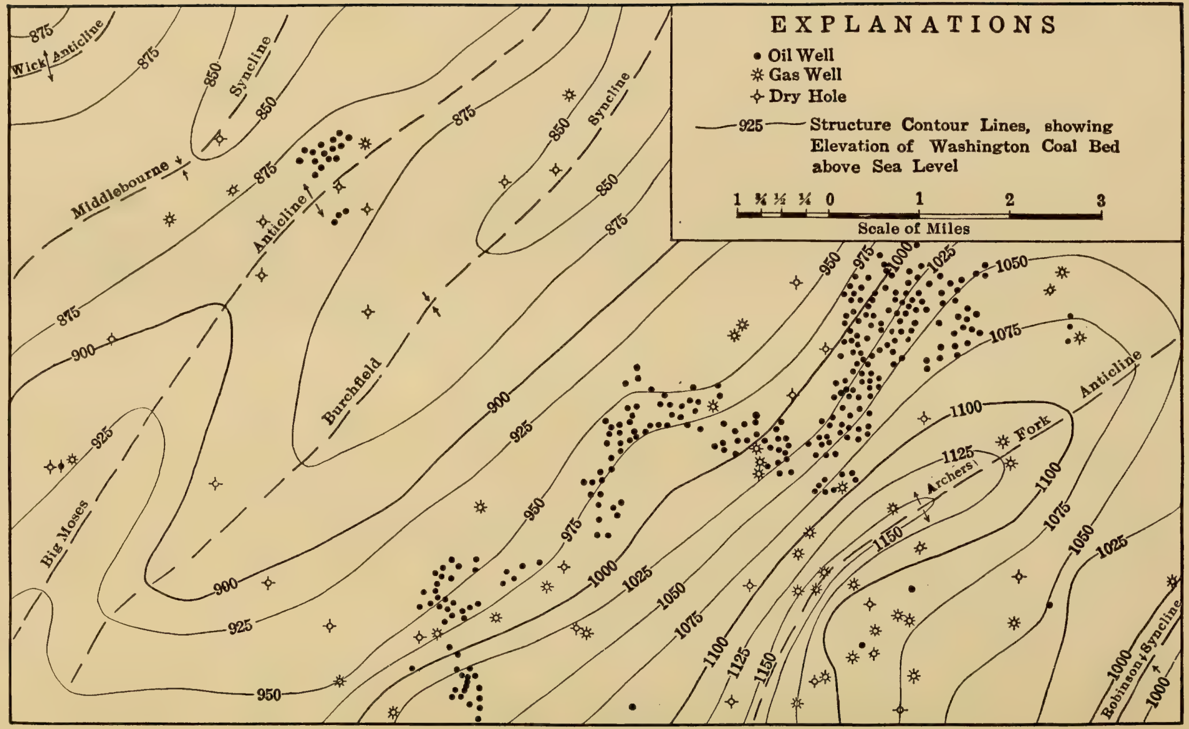
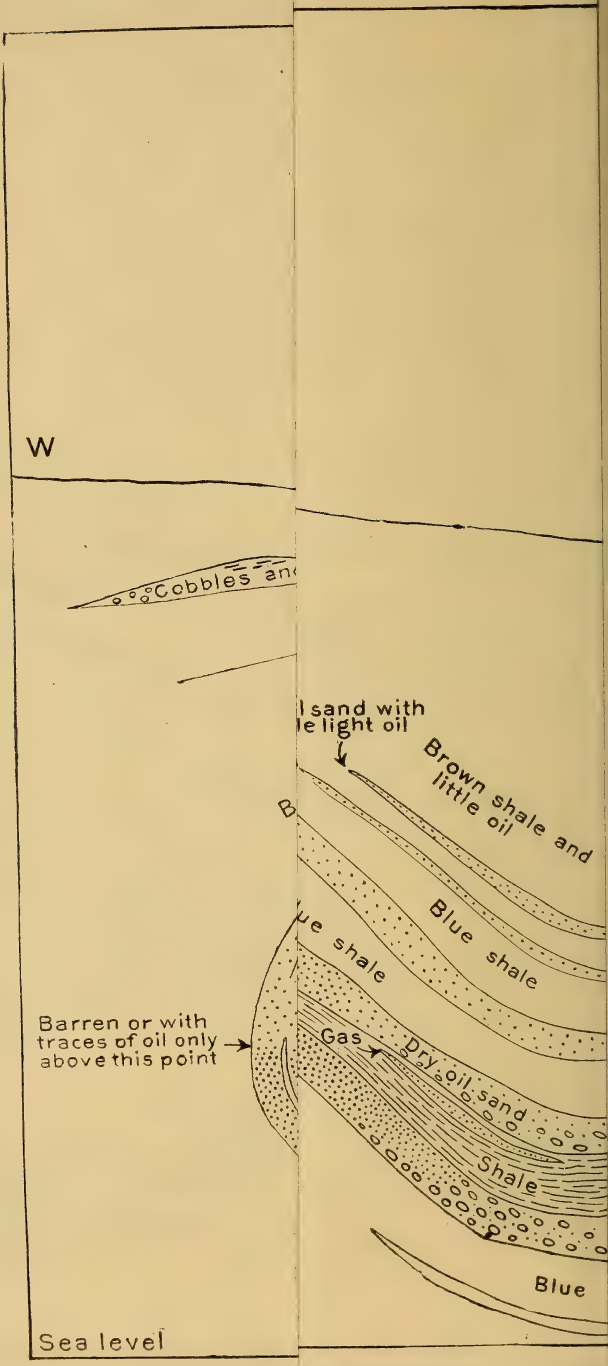

EXPLANATIONS
● Oil Well
✲ Gas Well
✧ Dry Hole
925 Structure Contour Lines, showing Elevation of Washington Coal Bed above Sea Level
1 ¾ ½ ¼ 0 1 2 3
Scale of Miles
Wick Anticline
Middlebourne
Anticline
Syncline
Burchfield
Big Moses
Archers Fork
Anticline
Robinson Syncline
875
850
900
925
950
975
1000
1025
1050
1075
1100
1125
1150

FIGURE 4.—*Structure Map of a typical Oil and Gas Field in West Virginia*

This is illustrative of Subclass II (*b*). The gas field corresponds with the crest of the anticline, while the oil field is midway between the anticline and syncline. Contour interval, 25 feet. (After I. C. White and Roy V. Hennen: Report of the West Virginia Geological Survey, 1911.)


W
Cobbles an
l sand with
le light oil
Brown shale and
little oil
B
Blue shale
ue shale
Barren or with
traces of oil only
above this point
Gas
Dry oil sand
Shale
Blue
Sea level

—*Hypothetical Section across sou*

nce of oil according to Subclasses

in this country is the Cincinnati anticline, in which immense reservoirs of oil and gas have been developed and exhausted from the Trenton limestone. Owing to the broad areas under which oil is found in the Cincinnati anticline, the chances of success in drilling were originally much better than in other fields. The pools in the Clinton sand in Ohio are situated along the eastern flank of the Cincinnati anticline, but these pools belong under Class III. A cross-section of the Trenton limestone field appears in figure 2. Another great geanticline, which is important for natural gas development, is that in western Canada, extending north from the International Boundary to the Athabasca River.[31]

Subclass II(d)—Overturned folds.—Examples of oil and gas occurring in connection with overturned folds are not common, but instances are conspicuous in California, as shown by Arnold and Johnson (figure 5).[32] In this case the overturned formations are the retaining ones, while the oil is contained in the synclinal portion of the sand. Other instances are reported from Galicia and Roumania.

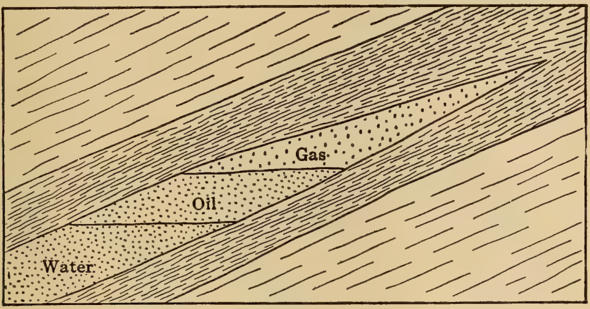


FIGURE 6.—*Ideal Section in a pinching Sand*

Showing the relations of gas, oil, and water according to Subclasses II (*e*) and III (*d*)

Subclass II(e)—Lenticular nature of the sands.—In all types of structure there are numerous instances where the sandstones or other porous oil-bearing beds are locally too hard or close grained to hold the oil or they pinch out laterally between shale beds. It is necessary, therefore, to add a new subclass under Classes II and III to include these lenses. A typical example is shown in figure 6, where the sand pinches out toward the anticlinal crest, causing the gas to collect on the side of the anticline

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[31] F. G. Clapp and L. G. Huntley: Petroleum and natural gas resources of Canada, by F. G. Clapp and others, vol. ii, 1915, pp. 271-272.

[32] Ralph Arnold and Harry W. Johnson: Bull. 406, U. S. Geol. Survey, 1901, p. 97.

W
E
Brea
Cobbles and asphaltum
Axis of Shamrock anticline
Oil sand
Dry sand and shale
Brown shale
Dry oil sand
Rich oil sand
Brown shale
Brown shale with oil
Brown shale
Dry
Oil sand
Brown and blue shale
Oil sand with little light oil
Gas
Brown shale and little oil
Brown shale
Gas
Gas
Productive below here
Blue shale
Blue shale
Productive oil sand
Rich oil sand
Shale
Oil sand
Brown shale
Brown shale with oil
Oil sand
Dry oil sand
Barren or with traces of oil only above this point
Rich oil sand
Brown shale
Oil sand
Rich oil sand
Brown shale
Brown shale
Gas
Dry oil sand
Shale
Good oil sand
Rich oil sand
Dry oil sand
Blue clay
Blue clay
Brea
Brea
Axis of Dabney anticline
Oil sand
Oil sand
Water sand
Oil sand
Oil sand
Brown shale and asphalt
Brown shale and clay
Dry sand with little asphaltum
Blue shale
Sand and gravel
Tar sand
Shale and clay ?
McKITTRICK VALLEY
Vertical and horizontal scale
0
200
400
600
800
1000 Feet
Sea level
Sea level

FIGURE 5.—*Hypothetical Section across south End of McKittrick Oil Field in California*

It illustrates occurrence of oil according to Subclasses II (*d*), III (*d*), etcetera. (After Arnold and Johnson)

and the oil still lower on its flank. Another example, after Arnold, is shown in figure 7.

CLASS III—MONOCLINAL STRUCTURE

General discussion.—The question arises whether to use the well known term "monocline" or the recently suggested one, "homocline." We find, on consulting Webster's New International Dictionary (1910), that homocline does not appear, while monocline is defined as "having, or pertaining to, a single oblique inclination; as, a monoclinal fold or flexure." A monoclinal flexture as distinguished from a fold is defined, quoting from W. B. Scott, as "a single, sharp bend connecting strata which lie at different levels and are often horizontal excepting along the line of flexure." A monoclinal fold, therefore, is any obliquely inclined series of strata dipping entirely in one general direction.

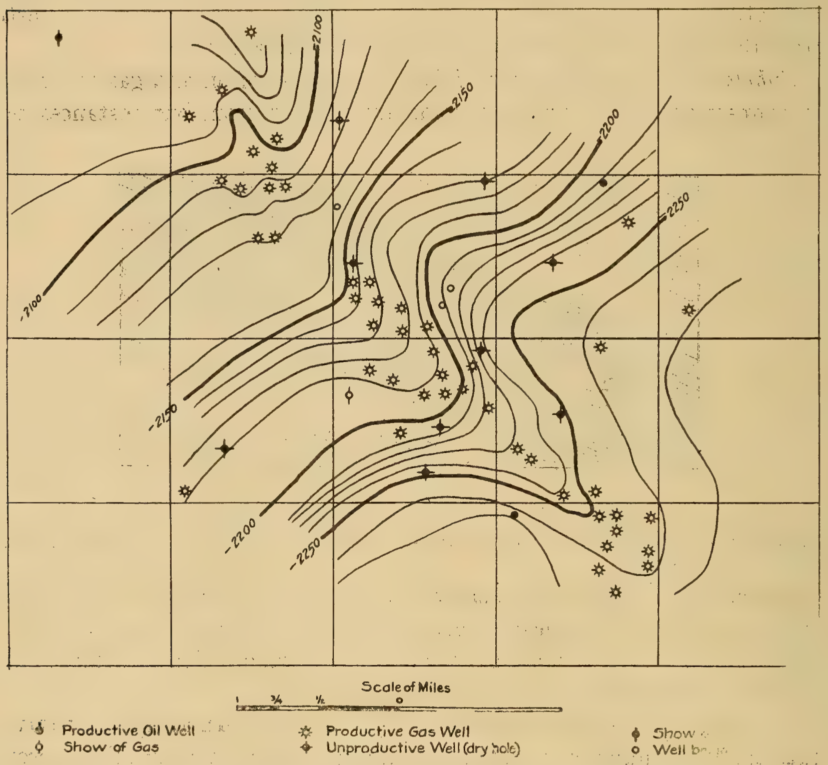
2100
2150
2200
2250
-2100
-2150
-2200
-2250
Scale of Miles
1
3/4
1/2
0
Productive Oil Well
Show of Gas
Productive Gas Well
Unproductive Well (dry hole)
Show
Well b

FIGURE 8.—*Structure Map of Gas Pool in Clinton Sand near Wooster, Ohio.*

Showing occurrence on a monoclinal nose according to Subclass III (*a*). Contour interval, 10 feet. (After C. A. Bonine, in Bulletin 621-H, U. S. Geological Survey, 1915)

Coalir

s III.

NW
D
Surface of ground
SE
D
Shale and sand
Shale and sand
Zone B
Shale and sand
Shale and sand
Sea level
Sea level
Shale and sand
Shale and sand
Zone B
Shale of Tejon (Eocene)
Shale and sand
Zone B
Zone D
Productive oil sand
Tar, gas, and dry oil sand
Water sand
Sulphur-water sand
Horizontal and vertical scale
200
0
200
400
600
800
1000 FEET

FIGURE 7.—*Hypothetical Section through the Coalinga Oil Field in California*

It illustrates the occurrence of oil according to Class III. (After Arnold and Anderson)

Notwithstanding the old definition, however, a new term—homocline—was introduced by Daly,[33] to apply to monoclinal folds (those having a single oblique inclination). This term has apparently been tacitly adopted by some petroleum geologists; but since the term monocline, meaning the same thing, appeared in our original classification, and has been generally applied before and since, no change is being made here. This term monocline was proposed by W. B. and H. D. Rogers in 1842, and since oil men have, by the geologists' persistent efforts, finally been educated to its use, the term homocline, while valuable in a scientific geologic sense, would in this classification accomplish no practical results. Monocline is used by Anderson and Pack in a recent bulletin,[34] where it is defined, as "in conformity with general usage, to mean a succession of beds dipping in one direction."

A monoclinal dip is seldom, if ever, perfectly uniform for many miles continuously, and it commonly has many changes of dip in short distances. Figures 8 and 9 are examples of monoclinal structure in Ohio, where one of the best known monoclines exists, the "lay" of the productive sands being represented by structure-contour lines. The rate of dip ranges from 20 to 200 feet per mile, according to locality. The steeper dips are generally confined within small areas, while the gentler ones are frequently uniformly continuous for many miles.

Judging by our detailed surveys, the evidence seems conclusive that the oil has been widely disseminated in the porous strata, and ultimately accumulated at favorable positions where the regularity of the dip is interrupted locally. Gas, in such cases, has collected on the up-dip side, where the sand is interrupted by pinching out, according to Subclass II(*d*), or by local flattening, according to Subclass II(*c*). Oil has collected on the down-dip side, generally where the change in rate of dip is most pronounced. In the Bremen pools of Ohio the most productive oil wells are situated at the points of greatest change in the rate of dip. Since the sand in those pools is perfectly dry, the accumulations are presumably due to catchment of the descending oil by these interruptions during the process of lowering of the original water level in the sand.

Cause of monoclinal accumulations.—In searching for the cause of the accumulations of oil such as the Bremen, Straitville, Junction City, Mingo, Cadiz, and other pools in strata of monoclinal dip in Ohio, and in similar but less familiar fields in Kansas and Oklahoma, the first step was the collection of numerous well records and data from which to determine whether the porous character of the productive sands was limited to the productive areas, whether the internal character changed in any way so as to make it incapable of holding oil, whether the sand disappeared on the borders of the pools, or whether the areas of productivity were independent of these features.

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[33] R. W. Daly: Canada, Dept. of Mines, Geol. Survey Memoir 68, p. 53.

[34] Robert Anderson and Robert W. Pack: Bull. 603, U. S. Geol. Survey, 1915, p. 109.

During the first field-work done in regions of monoclinal dip, many years ago, data were obtained which subsequent evidence in many fields has not refuted—that is, data indicating that the gas, oil, water, and dry areas in a persistent sand horizon are, as a rule, independent in their general distribution of the character or thickness of the sand. Some dry holes are found, even in the center of the best pools, due to the thinning out or hardening of the sand locally, and holes having sand of these characteristics exist also in extensive dry areas; but among the hundreds of dry holes drilled to the Clinton sand east of the main gas belt in Ohio the great majority contain sand to all appearance as suitable in texture and thickness as most of the sand in which oil and gas are found. This

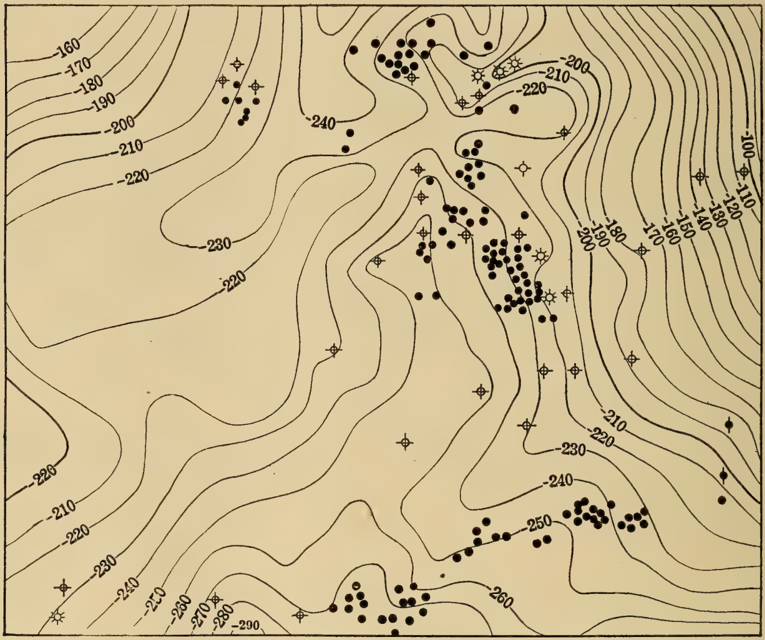

FIGURE 9.—*Map illustrating the Occurrence of Petroleum on structural Terraces, in southeastern Ohio, according to Subclass III (c)*

After Griswold and Munn. For explanations see figures 3 and 8. Contour interval, 10 feet conclusion was reached in part by personal examination of samples and in part by talking with the drillers of the wells.

The question then arose whether hydrostatic or hydrologic conditions may not have been responsible for the position of the accumulations. To a certain extent this seemed to be true, since many of the oil pools in the Berea sand are bounded on their down-dip sides by pools of salt water; and following the hypothesis further, it was found that still farther down the dip other oil and gas pools existed, which in turn were usually bounded by salt-water pools on their down-dip sides. So far as could be learned, the position of the water pools, rather than the oil or gas pools, was determined by a retaining terrace or barrier of close-grained sand. The best known examples of this condition are in the Pan-Handle of West Virginia and in Oklahoma and Kansas, where pool after pool has been discovered by the oil men, the last to be discovered being farthest down dip. All, however, appear to be dependent predominantly on structure.

A similar condition of affairs was found in the development of the Clinton sand fields of central Ohio. The Bremen pool is situated down dip from the main gas belt, and still farther down dip is the Junction City pool. Similar relations prevail throughout the Clinton fields. Between all of the pools barren areas exist for short distances. While it is true that in some of these barren areas the Clinton sand was found to be locally hard, thin, or close, it is equally true that in the great majority of cases it maintains its wonderfully uniform character without regard to whether it holds oil or is dry.

One other important factor remained to be considered, namely, *structure.* When this was worked out in detail for any particular field, the conclusion was reached in nearly every case that the peculiar structures associated with the oil pools are too multifold in their correspondence to be caused by mere chance agreements. *When considered in a broad light, the common feature of most oil pools on monoclinal dips seems to be their occurrence at points of interruption in the general rate of dip.*

Types of interruption.—On a monoclinal dip there seem to be two main types of interruptions: (1) Those due to *longitudinal* warping, parallel with the direction of strike of the sand, and (2) those due to lateral warping, parallel with the direction of dip. The last-mentioned type produces structural "noses," as illustrated in figure 8. The first type of interruption produces a "ravine" or "notch" in the monoclinal slope, such warpings being common in the Ohio fields. The ravine-like structure, being a conspicuous type of abnormality in monoclinal dip, seems to be very favorable for oil occurrence where the sands are dry.

Actual determinations of the structure of the Clinton sand under extensive areas have shown that where types (1) and (2) intersect, as in many localities in the Bremen pools of Ohio, the largest accumulations of oil are found.

It is evident that fields of commercial importance will not commonly occur in regions of *plane* monoclines any more than they will in *absolute* aclines, since no factors of separation exist, with the one reservation, that if the sands contain water, as most sands do at some locality or other, an oil pool is likely to rest on it. However, some degree of inclination is necessary to cause the separation, and it is found in practice that where this dip is less than half a degree the separation is so incomplete as to cause few, if any, commercial pools. Manifestly, the only way to locate an oil pool on a plane monocline is to drill for it, since the surface structure will afford us no aid.

In the great monocline of central Ohio the water level has never been found in the Clinton sand, although wells 4,000 feet deep have been drilled. It is believed by geologists and the scientific oil men that when this water is ultimately found, somewhere beneath eastern Ohio, a large pool of oil will be found resting on it, similar in its trend to the great central Ohio gas field.

Subclass III(a)—Monoclinal noses.—Attention was first called to the monoclinal nose type, but without any particular name, by the present writer in 1910.[35] This type of structure is very common in the gas fields of central Ohio, and figure 8, from a bulletin on the Wooster field,[36] will illustrate it. Examples are also frequent in the North Texas fields, and unfortunately have been confused with anticlines by some undiscriminating persons.

This type may be considered as a less prominent form of Subclass III(*c*), in that the terrace is not a well defined one. While it has been noticed by the writer mostly in Ohio and Oklahoma, a number of examples have been reported by Gardner and others in Kentucky.

Subclass III(b)—Monoclinal ravines.—The term "structural ravine" was perhaps first used by the writer in 1911,[37] having exactly the same relation to an inclined sand as a topographic ravine would have in a sloping hillside. In the revised classification the term is changed to "monoclinal ravine," as being somewhat more specific.

Subclass III(c)—Structural terraces or "arrested anticlines."—Terrace structure was first described by Orton in 1866.[38] The terraces described by him were in the Findlay field of northwestern Ohio, where the oil and gas existed in two terraces, separated by a short monocline. The upper terrace yielded dry gas, the lower one yielded oil and water. While structural terraces might be described under Class II, they are more properly a variety of monoclinal structures, and an extreme case of Subclass III (*a*) or (*b*). They were named by Orton[39] "arrested anticlines," and the Macksburg field of southern Ohio was cited by him as an example. The terrace structure of the Macksburg field was first recognized and described by Newhall in the same volume.

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[35] Economic Geology, vol. v, no. 6, 1910, p. 508, fig. 53.

[36] C. A. Bonine: Bull. 621-H, U. S. Geol. Survey, pl. xiii.

[37] Econ. Geol., vol. vi, no. 1, p. 10.

[38] Edward Orton: Science, vol. 7, p. 563.

During the past two decades hundreds of structural terraces have been discovered in southeastern Ohio, Kansas, West Virginia, and to some extent in other States, and most of them are available for oil and gas development. Generally, though not always, the structure can be practically determined from the geology of the surface without the need of borings until one is ready to make his test. Other good examples of terrace structures and relations of oil to them have been described by Griswold and Munn in Jefferson County, Ohio,[40] and figure 9 is an illustration of this class of structure taken from their report.

Subclass III(d)—Accumulations on monoclines due to thinning out or change in texture of the sand.—While it has been said that texture or dying out of the sand is not responsible as a rule for the exact positions and limits of oil pools on monoclinal dips, there are exceptions to this statement. In the Louisiana fields some of the oil and gas accumulations are contained in lenticular sands, which thin out or grade into shale laterally.[41] This appears to be much more frequently true in Kansas, where the sands diminish in importance northward, than it is in Oklahoma, where they are more persistent. In such cases the relations of oil, gas, and water contained in the sands are commonly similar to their general relations in any other monocline, except that the outlines of the pools are bounded by the extent of the sands (see figure 6). Similar lenticular sands are abundant in the California fields, where the structural relations are described and illustrated by Arnold.

Doubtless a great number of cases of this type exist; but the best known is that of the so-called Clinton sand of Ohio (in reality the Medina sand), which rises from a great depth in the Appalachian basin and gradually thins out as it approaches the surface in central Ohio, so that it never reaches the surface, the feather edge being bounded by shale, furnishing an ideal substitute for an anticline and being a repository of one of the greatest gas fields in the world, on the lower border of which are the Bremen, Wooster, Straitsville, and other oil fields. A cross-section of the west side of the Appalachian basin, illustrating Subclass III(*d*), is shown in figure 2.

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[39] Geology of Ohio, vol. 6, 1888, p. 94.

[40] Bull. 318, U. S. Geol. Survey, 1907.

[41] G. D. Harris: Bull. 429, U. S. Geol. Survey, 1910, pp. 128-129.

Oil occurs in lenses in either of two ways: (1) in the upper end of a pinching-out lentil, and (2) where the latter is dome-shaped, in the upper part of this dome. Doubtless a large number of instances of the second class exist, but they form local phenomena of pools rather than a cause of an independent pool.

CLASS IV—QUAQUAVERSAL STRUCTURES, OR "DOMES"

General discussion.—In the classification of oil pools, the subdivision entitled "Quaquaversal structures" is considered to include those structures in which the oil sand dips away in all directions from a central point, including the saline domes of Louisiana, certain domes in Oklahoma and West Virginia, the basalt plugs of Mexico, and the perforated and non-perforated salt domes of Roumania and Hungary.

Subclass IV(a)—Anticlinal bulges or "cross-anticlines."—This type of structure merges with those described in Subclasses II(*a*) and II(*b*) of the classification, since practically all anticlines consist of alternate contractions and bulges where their crests are respectively depressed or elevated. The term "cross-anticline" has been sometimes applied to these domes or bulges, but not always correctly so—as, for instance, at Jacksonville, Greene County, Pennsylvania[42]—where the deepest part of the Ninevah syncline lies directly opposite the highest part of a dome on the Washington anticline.

This is one of the types to which the anticline theory, as originally promulgated by I. C. White, can be applied without modification. In the illustration mentioned, the strata dip northwest toward the Ohio River syncline, southeast toward the Ninevah syncline, and northeast and southwest it plunges into a long structural fold which extends from the vicinity of Cannonsburg, Pennsylvania, southwest into Wetzel County, West Virginia. In other words, the Jacksonville dome or bulge has the shape of an inverted basin.

Anticlinal bulges are of all shapes and sizes, but those of great length would hardly be recognized as domes and are not here considered, since they belong strictly to Subclass II(*a*). Anticlinal bulges exist in many places in Pennsylvania and West Virginia, in a few counties in Ohio, and are frequent in Wyoming. The fact that the Wheeler and Healdton pools in southern Oklahoma and the Petrolia pool in northern Texas owe their position to distinct doming of the strata seems to have been first mentioned by Gardner,[43] the structure of the Petrolia pool being originally worked out by Udden and Phillips.[*] The anticlines and domes have since been mapped for the United States Geological Survey and by the author of this paper, as well as many other geologists in private work. The doming is supposed to have taken place both before and after the deposition of the Permian red beds, which, near the Arbuckle and Wichita Mountains, lie unconformably on the Pennsylvanian series. Oil exists both in the Pennsylvanian and Permian.

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[42] F. G. Clapp: Rogersville folio, No. 146, U. S. Geol. Survey, 1907.

Subclass IV(b)—Monoclinal bulges.—This type is frequently confused with the anticlinal-bulge type, but is quite distinct in structure. Anticlinal bulges are expansions and elevations in the crest of definite anticlines or continuous folds, while monoclinal bulges are domes that rise with apparent irregular spacing on a monoclinal slope in which structures of Class III also exist. In Subclass IV(*b*) the monoclinal structure gives place locally to a quaquaversal structure. On the great monocline of central Ohio few domes are known in the Clinton sand and are frequently absent in the Berea for long distances. In Kansas and Oklahoma, however, monoclinal bulges form one of the commonest forms of structure, an illustration of which is given in figure 10. Since in that part of the country the sands are commonly saturated with water, the oil and gas both occur on the dome itself.

Subclass IV(c)—Closed saline domes.—History of saline dome developments.—The credit of discovering that this form of domes contains oil is due largely to Captain Lucas,[44] who in 1901 drilled a well at Spindletop, Texas, and discovered a famous field. As early as 1894 diamond-drill borings had been made by him at Jefferson Island, Belle Isle, Weeks Island, and Anse La Butte, Louisiana, discovering salt masses of limited area, but of great depth. In 1899 a paper on this subject was first published by Lucas[45] and the discoveries were confirmed by a paper published by Hill in 1902.[46] The last-mentioned writer says:

> "Before the discovery of Spindle Top there was only one man whose ideas—although not yet coordinated into a theory—approximately fitted the observed conditions. Of course, I refer to Captain Lucas, who, in his explorations of the Coastal Plain, seeking successively salt, sulphur, and oil, had observed the

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[43] James H. Gardner: Econ. Geol., vol. 10, no. 5, 1915, pp. 422-434.

[*] J. A. Udden and D. McN. Phillips: Tex. Univ. Bull. 246, 1912.

[44] A. F. Lucas: The dome theory of the Coastal Plain. Science, n. s., vol. 35, no. 912, June 21, 1912, pp. 961-964.

[45] Rock-salt in Louisiana. Trans. Am. Inst. Min. Engrs., 1899; also Journ. Ind. and Eng. Chemistry, vol. 4, no. 2, Feb., 1912.

[46] R. T. Hill: Journ. Franklin Inst., vol. 154, Aug. and Oct., 1902, pp. 143, 225, 263.

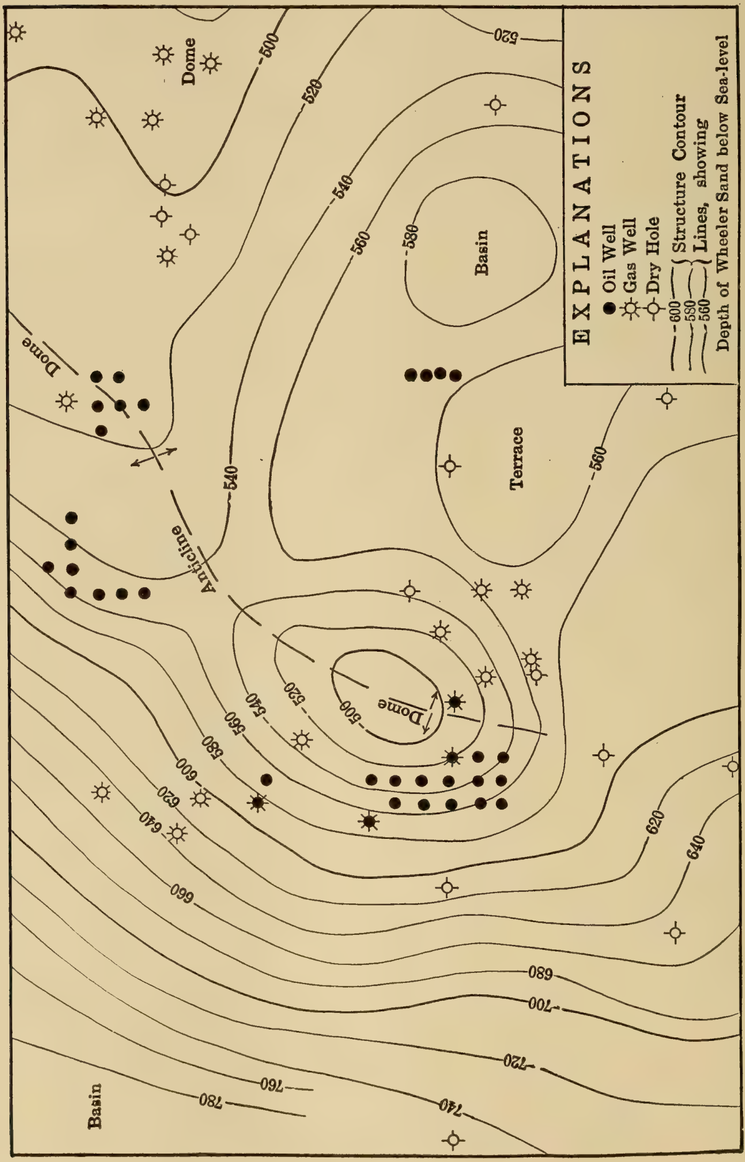
EXPLANATIONS
● Oil Well
☼ Gas Well
Dry Hole
600
580
560
Structure Contour Lines, showing Depth of Wheeler Sand below Sea-level
Dome
Dome
Dome
Anticline
Basin
Terrace
Basin
500
520
540
560
580
600
620
640
660
680
700
720
740
760
780

FIGURE 10.—*Structure Map of a Locality in Osage County, Oklahoma*

Indicating the monoclinal bulge type, Subclass IV (*b*). Contour interval, 20 feet. Scale: 1 inch = 1 mile associations of oil, sulphur, sulphuretted hydrogen, gas, gypsum, dolomite, and salt, constituting collectively what might be termed the oil-phenomena representing a group of secondary products as distinguished from the mother-strata or sediments out of which they have been produced. Moreover, so far as I am aware, he first pointed out the existence of anticlinal hills in the Coast Prairie and their connection with the oil-phenomena. . . . Captain Lucas early noted that sulphuretted hydrogen escaping from the earth under certain conditions deposited sulphur in crevices near the surface. Such phenomena he observed at Spindle Top before commencing his well. At High Island, Galveston County, Texas, work was temporarily suspended on a well hole and the orifice stopped with hay in order to prevent obstructions from debris. Afterward when the plug was withdrawn the hay was found to be imbedded in a matrix of sulphur, undoubtedly deposited by the escaping gas. . . . No topographic surveys have ever been made of any portion of the Coastal Prairie, and hence the slight irregularities of its contour are discernible only with difficulty. Until Captain Lucas's investigations, certain low elevations which have since become the most important features of the landscape were hardly noticed. I allude to low swells or hills, such as Spindle Top, which occur here and there and now attract attention from their supposed relation to the occurrence of oil beneath them. . . . In the generally monotonous monoclinal structure there are a few wrinkles or small swells likely to escape the eye of even the trained observer, and yet of a character which may have an important bearing on the oil problem. These are the circular or oval mounds already described which were first recognized by Captain Lucas. When he pointed out Spindle Top hill to me, my eye could hardly detect it, for it rises by gradual slope only ten feet above the surrounding prairie plains. I was still more incredulous when he insisted that this mound, only 200 acres in extent, was an uplifted dome. But Captain Lucas said that I would be convinced of the uplift if I could see Damon's mound in Brazoria County. In August, 1901, I visited that place and then returned for a second look at Spindle Top and was convinced that if these hills are not recent quaquaversal uplifts no other known hypothesis will explain them."

Quoting from Lucas at a later date:[47]

"At Jefferson Island pure rock-salt was penetrated to a depth of twenty-one hundred (2,100) feet without finding bottom, and at Belle Isle rock-salt, having a depth of twenty-seven hundred and forty (2,740) feet (pierced in 1907), was discovered with paraffine oil and large lenses of pure sulphur.

"The successful results attained by his explorations in Louisiana led the writer to extend the study of a nascent 'dome theory' into Texas and to apply it to the various phenomena occurring on Spindle Top, a low elevation of only ten to twelve feet above the surrounding prairie, and to drill finally on this dome against the advice of his friends, with the well known result that the largest well ever discovered in the United States and variously estimated at from 75,000 to 100,000 barrels per day had its birth on the tenth day of January, 1901.

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[47] Science, n. s., vol. 35, no. 912, June 21, 1912, pp. 962-963.

"The success of this well demonstrated the possibility of attaining economic results by drilling for oil, gas, and sulphur on the domes of the coastal plain. This theory held good throughout the hundreds of wells drilled around Spindle Top in the effort to extend the area laterally, without results, however, for it was subsequently proved that if the original well had been located only sixty-five feet further to the northwest there would not have been a discovery well.

"There are scattered throughout the Texas Coastal Plain many well known domes which have been prospected directly or indirectly by the writer, the most important of which are known as Saratoga, Sour Lake, Big Hill, High Island, Damon Mound, Kaiser Mound, Barber Hill, Hoskins Mound, and Bryan Height. In the last named mound the writer found in 1901 hydrogen sulphide under heavy pressure and also native sulphur, which is now being heavily exploited by a New York syndicate, which hopes to make this equal to the sulphur mines of Louisiana. Whether or not this mound is also a salt dome remains to be proved by deeper drilling."

Spindletop is the best known of the saline dome type of pools. This dome rises only 12 feet above the surrounding prairie and the surface is only about 235 acres in extent. Although prospecting had been done in 1882, 1885, and 1888, the drillers were prevented by alternating beds of quicksand and gravel from going deeper than 300 feet. Lucas made the final effort and reached the oil rock at 1,120 feet, the pressure being so great that the 4-inch drill pipe was shot from the well, after which there was a great rush of muddied water, followed by large fragments of dolomite and fossils. The well then settled to a steady flow of oil, which rose to a height of about 200 feet through a 6-inch pipe, and flowed continuously for ten days, being estimated to have flowed about 750 barrels in that time. The oil was very offensive in odor, saturated with hydrogen sulphide and sulphur dioxide, so that all houses within a radius of several miles which were painted with white lead, as well as all silver coins, spoons, and other silver in them, were blackened.

This type of quaquaversal structure was described by Hayes and Kennedy in 1903[48] and more fully by Fenneman in 1906.[49] The saline domes of Louisiana were described by Harris in 1908,[50] 1909,[51] and 1910.[52] The structure is typical of most of the fields in Louisiana and Texas; in fact of most fields in the United States situated within 100 miles of the Gulf of Mexico. The Caddo field, Mexia field, the north Texas fields, and some of the southwest Texas fields are not included in this type.

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[48] C. W. Hayes and William Kennedy: Oil fields of the Texas-Louisiana Gulf Coastal Plain. Bull. 212, U. S. Geol. Survey.

[49] N. M. Fenneman: Oil fields of the Texas-Louisiana Gulf Coastal Plain. Bull. 282, U. S. Geol. Survey.

[50] G. D. Harris: Rock-salt. Bull. No. 7, Rept. of 1907, Geol. Survey of La., 1908.

[51] Geological occurrence of rock-salt in Louisiana and East Texas. Econ. Geol., vol. 4, no. 1, 1909, pp. 12-34, 8 figs.

[52] Oil and gas in Louisiana. Bull. 429, U. S. Geol. Survey, 1910.

Topography and structure.—In southern Louisiana are five prominent elevations known as the "Five Islands," or the "South Islands," which constitute the most conspicuous landmarks in hundreds of miles along the coast of the Gulf of Mexico.[53] They rise from a few feet to 200 feet above marsh level and in area range from 200 to 1,500 acres. They have been frequently discussed in literature. Salt is found in all the Five Islands except Cote Blanche.

It should not be supposed, however, that every structure which is a saline dome geologically is evinced on the surface by a topographic dome. While instances like those mentioned above exist of the occurrence of mounds or small hills overlying the geological domes, the topographic dome is not an essential of the type, and many saline dome pools are situated where the surface lies practically flat.

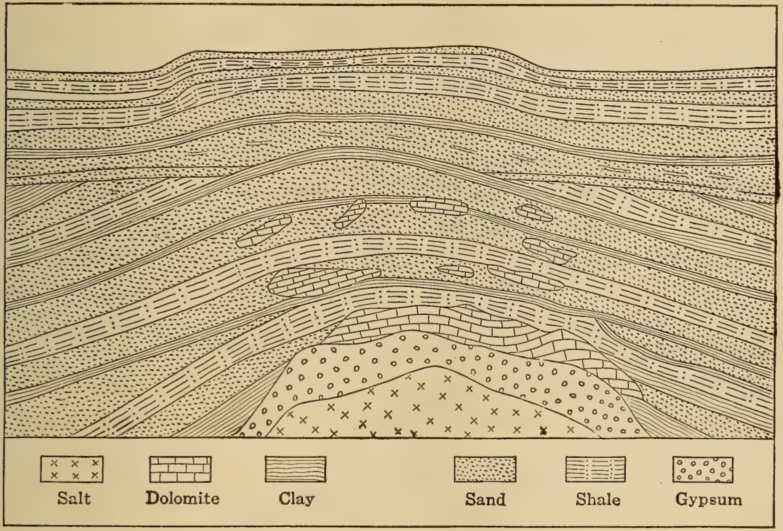

FIGURE 11.—*Cross-section of a typical Saline Dome Oil Field in Texas*
After Hager. Subclass IV (*c*)

The configuration of the strata in saline domes is a matter of interest and great importance, as the structure is very different from the normal southeastward dip of the Cretaceous and Tertiary beds underlying the Gulf Coastal Plain of Louisiana and Texas. Whether or not there is any particular surface topography indicative of a dome in the locality, there is a very marked geological protuberance consisting of a sudden upward bending of the strata as they approach the edge of the dome, so that they may stand practically vertical on its circumference. An uplift of several thousand feet in an area a mile across is not uncommon. While no Cretaceous beds of normal structure reach the surface in Louisiana, there are several saline domes in which these formations have been uplifted to the surface in limited areas. Beneath the Cretaceous beds and interlaminated with them in the center of the domes are found extensive deposits of rock-salt, sulphur, gypsum, and sometimes other minerals.

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[53] A. F. Lucas: Trans. Am. Inst. Min. Engrs., vol. 29, p. 464.

The term "dome," therefore, refers to the geological structure, as illustrated in figure 11, and in the Gulf Coast oil fields the underlying formations are domed, whether the surface is so or not. At Spindletop the rock structure has been carefully determined on the basis of well records and found to have a form similar to that illustrated. The cross-sections of all saline domes, so far as determined, show a similar, more or less dome-like form, although great differences exist in local conditions. As a rule, sands and gravels are penetrated for several hundred feet in depth, then limestone or dolomite is encountered, below which sulphur, gypsum, and rock-salt are found. The character of these minerals is not supposed to have any effect on the existence of oil at the particular point; but the oil has been accumulated from the surrounding strata either because of a point of interruption formed by the upward doming of the sediments or because the breaking of the strata have allowed it to rise from below.

List of known saline domes.—Practically all the known saline domes except those discovered within the past eight years have been described and mapped by Veatch[54] and Harris.[55] The following list comprises some of the salines in Louisiana: Grand Cote (Weeks Island), Petite Anse (Averys Island), Belle Isle, Cote Blanche, Cote Carline (Jeffersons Island), Anse la Butte, Prairie Mamou (Jennings oil field), Welsh, Chicot (Pine Prairie), Sulphur, Vinton, Hacksberry, Negreet saline, Coal Bluff saline, Many, Bayou Castor saline, Browns saline, Cedar Bayou saline, Winnfield dome, Coochie dome, Drakes saline, Prices saline, Reyburns saline, and Bistineau saline.

Some of the saline domes in Texas are as follows: Davis Hill, Saratoga, Batson, Big Hill, in Jefferson County; Sour Lake, Spindletop, Big Hill, in Matagorda County; Dayton, Humble, Barbers Hill, High Island, Blue Ridge, Hoskins Mound, Damons Mound, Kaisers Hill, Bryan Heights, Grand saline, Palestine, Steens saline, Brooks saline, Grahams saline, Markham, and Stivers saline.

Association of rock-salt and other minerals.—Salt is believed to exist in all domes of this subclass. The salt consists of 98 to 99 per cent sodium chloride, except at Belle Isle, Louisiana, where it is saturated with oil. Galenite and sphalerite were also found at Belle Isle in a well drilled on the center of the dome; pyrites has been reported and gypsum and sulphur are common accompaniments. Borings made for oil and sulphur at Belle Isle have discovered limestone, sulphur, and escaping waters charged with hydrogen sulphide and sulphur dioxide, but the oil drawn from these wells gives no indication of sulphur.

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[54] A. C. Veatch: La. Geol. Survey, Rept. 1902, pp. 41-100.
[55] Bull. 429, U. S. Geol. Survey, 1910.

In Spindletop dome certain wells have passed through oil rock and gypsum and penetrated the salt core. The dolomitic oil-bearing rock is estimated as 75 to 150 feet thick. Large cavities exist in the dolomite, their size being estimated by large fragments shot from the wells. In some cases drillers report that the tools have dropped several feet into cavities which undoubtedly act as oil reservoirs. A test near the discovery well at Spindletop entered gypsum at 1,200 feet, rock-salt at 1,650 feet, and ended at 1,900 feet from the surface. While in some saline domes oil has not been found in commercial quantities, it is known in great quantity in many of them, and nowhere else in extreme southern Louisiana and southern Texas.

Apparent absence of salt in some domes.—In a few of the Gulf Coast domes no rock-salt has yet been discovered. One of these instances is in the Jennings field, at Prairie Mamou, Louisiana, where oil was found at a depth of 1,800 feet. In the Welsh pool of Louisiana there is no topographic evidence of doming and no salt has yet been found; but, as at Jennings, it is believed to exist. The best wells at Welsh are about 1,000 feet deep. At Sulphur, Louisiana, also known as Bayou Choupique, oozings of petroleum and gas led the Louisiana Oil Company to drill as long ago as 1868. Clays, sands, and gravels were penetrated for 434 feet, and then massive gray limestone 60 feet in thickness was encountered. Beneath this limestone alternate layers of pure sulphur and limestone were found throughout a thickness of 260 feet, and still below were gypsum beds with occasional layers of pure sulphur. Rock-salt is as yet unknown at Sulphur, which is one of the great sulphur mines of the world. Since the profitable working of the sulphur was undertaken, there has been no serious attempt to exploit the oil, although heavy oil still flows from the upper strata into certain old test wells.

Distribution of saline domes.—Since the saline domes of the Gulf coast may not be conspicuous in the surface topography, and since the surrounding country is flat and without rock outcrops, the question is frequently asked whether anything can be done in those fields toward reliable predictions of the localities of occurrence of oil. While few attempts to do this have been made in a systematic way, there is no doubt that new fields in Louisiana and Texas are and will be predicted and discovered through a knowledge of the geology of the saline dome type and distribution of these structures.

This statement will be partly understood from the distribution of the saline domes along lines, sometimes perfectly straight and sometimes slightly curved, but which extend for many miles across the country. For instance, the Jennings oil field, Cote Carline, Petite Anse, Averys Island, Weeks Island, and Belle Isle lie on an absolutely straight line extending in a northwest-southeast direction; Anse la Butte, Pine Prairie, Negreet, and possibly one or two other salines lie on a similar line, approximately parallel to the first; Davis, Batson, Sour Lake, and Spindletop lie on a third line, having a similar direction, and a fourth line may be considered as connecting Dayton and Big Hill with several scums of oil which have been noticed floating on the Gulf of Mexico.

Moreover, there seem to be east-west lines of saline domes. The most important of these may be considered as connecting Anse la Butte, Jennings, Welsh, Sulphur, Sour Lake, and Big Hill. The first-mentioned northwest-southeast system connecting known domes was mapped by Harris, who also plotted a northeast-southwest system, but he does not recognize any east and west system. Harris considers the lines as constituting fault-lines and believes that the domes exist at the intersection of two faults.

The alignment of saline domes was first mentioned by Lucas.[56] It was perceived by Hayes and Kennedy,[57] who published a map showing possible lines of flexures or faults. This alignment was still further mapped by Harris.[58] The following is a summary of the arguments given by the latter to account for his faith in the theory of alignment:

1. The abnormal dips found along the southeast and northeast margins of the "Sabine Uplift" in northwestern Louisiana.
2. A number of the individual domes have an elliptical elongation. Two of these are the Winnfield and Coochie domes, which are longer northeast and southwest than in the other direction.
3. The Bistineau, Kings, Drakes, and Winnfield domes follow a line closely parallel to the outer margin of the Sabine uplift. In Texas, Andersons, Brooks, and Steins domes lie on a line parallel to the Balcones fault-line. High Island, Big Hill, and Spindletop also lie on a straight line, and Damon and Big Hill are on the projection of a line formed by three oil scums in the Gulf of Mexico. Probably the most conspicuous alignment in Louisiana consists of the series of domes which include the so-called Five Islands and the Jennings oil field. This line is roughly parallel with the Dayton-Big Hill line.

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[56] A. F. Lucas: Trans. Am. Inst. Min. Engrs., vol. 29, 1899, p. 463, fig. 1.
[57] C. H. Hayes and William Kennedy: Bull. 212, U. S. Geol. Survey, 1903, p. 144.
[58] Bull. 429, U. S. Geol. Survey, 1910.

4. Several so-called oil pools or scums of oil found on the surface of the Gulf of Mexico and plotted on the maps of the Hydrographic Bureau agree most remarkably in parallelism with the Five Islands.

5. Harris gives I. N. Knapp credit for the theory that the line formed by the Five Islands marks the location of a slight anticline, and Harris also states that the lower course of the Mississippi River from some distance above Baton Rouge to its mouth is determined by a syncline.

6. The strata of the Vicksburg formation seem to have been deposited in a V-shaped area whose limbs correspond with the two general systems.

7. The isogonic lines, or lines of terrestrial magnetism, are somewhat drawn together along the Sabine uplift, and this is believed by Harris to account for structural complications in that vicinity.

Harris grouped the supposed faults into two systems, one of them being roughly parallel to the Red River fault and the Alabama Landing fault, and the second roughly parallel with the Balcones fault in Texas. Since the evidence for the existence of these two series is far from conclusive, other possible groupings are suggested here which may or may not be true. A most interesting coincidence seems to be that the Anse la Butte, Jennings, Welsh, Sulphur, and Sour Lake domes are all situated on an east-west line, which appears perfectly straight and is more conspicuous than some of Harris's lines. It would be equally possible to plot a line from the Vinton, Spindletop, Barbers, Blue Ridge, and Welsh domes.

Whatever may be thought of the possibility of geological predictions in a flat country like southern Louisiana, it must be acknowledged that all the Gulf Coast pools are situated on the saline dome type of structure, and that many of these which contain oil lie on absolutely straight lines. In the entire Gulf Coast region not a single instance of success is recorded outside of a dome.

Origin of saline domes.—At least five different theories have been proposed at various times to account for the origin of the Texas-Louisiana domes. These are as follows:

1. That the domes are old Cretaceous peaks left as monadnocks by denudation which cut down the surrounding country. The limited horizontal extent of the salt masses is good evidence against this theory, as the domes are so isolated and local that they can hardly be parts of dissected ridges.

2. That they originated by gas pressure.

3. That they originated by water pressure.

4. That the strata were bent upward by laccoliths. This theory was first proposed by Hager,* and would appear to find support in the existence of volcanic plugs of Subclass IV(*e*) in the Coastal Plain of Mexico,

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* Lee Hager: Eng. and Min. Jour., vol. 78, 1904, pp. 137-139 and 180-183.

accompanied by many of the Texas type of phenomena. The Mexican plugs are arranged in straight lines in a manner similar to those of the saline domes. An interesting fact mentioned by Hill is that hot water has been encountered in several of the saline domes.

5. That the domes are situated at points of weakness overlying the intersection of fault-lines, and that heated waters, saturated with mineral in solution, have risen along these points of weakness under intense pressure, carrying with them the sodium chloride, sodium sulphate, etcetera, which were deposited near the surface by a relief of pressure and temperature. The deposition of these minerals was naturally attended by crystallization, the power of which is supposed to be so great that the entire overlying sediments were pushed upward and outward, forming the domes. This theory seems to have originally been formulated by Hill and is the one now most commonly accepted. In the vicinity of several of these domes are secondary centers of crystallization which have caused minor domes.

Harris believes, in the words of Washburne:[59]

> "That the amount of uplift of the strata is entirely inadequate to account for the amount of space occupied by the salt plugs, some of which have been penetrated by the drill nearly 3,000 feet without reaching bottom. He concludes, therefore, that the salt cores are not laccolithic or pluglike intrusions into the sediments, squeezed up from a great hypothetical salt bed in some lower formation, but rather that they have grown by crystallization at the places where they now occur and have not undergone much deformation. In other words, they are great cylindrical concretions of salt 1,000 feet or more across and over 3,000 feet high. He believes that the salt and the associated hydrocarbons were gathered by meteoric waters which percolated through the sedimentary strata and rose along the intersections of fissures, where the salt was precipitated because of the decrease in temperature and pressure. The decrease in pressure would cause but a negligible precipitation, practically nothing. Temperature is somewhat more effective, but Lindgren[60] says: 'As the solubility of salt increases only slightly with increase of temperature (35.69 per cent at 10° C.; 39.12 per cent at 100°; 44.90 per cent at 180°), only the increment could have been precipitated as the temperature of the ascending current was lowered, and hence the quantity of primary salt required by this hypothesis is incredibly large.' Let us assume that the solutions cooled as fast as the normal underground head gradient, or about 21° C. in ascending 2,000 feet. This would precipitate about 2 per cent of the total salt in a solution saturated at 100°. In other words, the salt cores would represent only about 2 per cent of the total amount of sodium chloride which had risen in the fissures, the rest having been carried beyond the top of the cores and lost. The salt cores in this country and Mexico number several hundred and their total

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[59] C. W. Washburne: Trans. Am. Inst. Min. Engrs., vol. 48, 1914, p. 691.

[60] Mineral resources of the United States (1913), p. 288.

volume is many cubic miles. The theory of Harris, if not modified, requires a supply of roughly 50 times as many cubic miles of salt.

"Yet the 'concretionary' theory of Harris has much in its favor, since it meets the mechanical requirements of the problem better than any other. The chemical difficulty can be met if the salt domes have been the loci of the escape of solutions carrying a common ion, either of sodium or of chlorine. Analysis of some volcanic waters shows an abundance of sodium chloride, and others of sodium sulphate or carbonate, but these do not meet the requirements of the present problem. From the character of the water and from the presence of secondary lenses of dolomite, one may infer that the precipitation was produced by the intermingling of concentrated salt solutions with brines rich in magnesium and calcium chloride. The former were probably derived mainly from the sedimentary strata, as suggested by Harris, but the latter probably rose from underlying plugs of olivine basalt which failed to reach the surface."

A late paper on the subject is by Norton.[61] The doming seems to have appeared first in late Cretaceous time and to have continued to a greater or less degree ever since. There is no doubt that the salt, sulphur, and gypsum are of later origin than the overlying sediments. Dumble states[62] that "the Sun mounds near Waller and Damons Mound are part Lafayette." The salt domes of Transylvania, which belong to the same type, are still forming, as evinced by studies of the present writer.

The great similarity between the bosses of salt and gypsum in Texas and Louisiana and those of basalt in Mexico has been mentioned by Garfias.[63] An ingenious European theory is that the saline domes of Germany, Transylvania, and Roumania have been caused by the lateral flowing of beds of salt into the domes owing to pressure in the overlying and underlying strata. So many theories, all with their advocates, and accompanied by equally as good arguments, go a long way to support the view that all our material theories must in time give way to something more tangible than materialism.

Subclass IV(d)—Volcanic plugs.—The best known examples of the volcanic neck type of quaquaversal structure come from the Coastal Plain of Mexico, which contains oil fields connected with many types of geologic structure, several of which are quaquaversal. The type in question consists of plugs or necks of basalt and similar rocks which rise through the Cretaceous and Tertiary sediments in the Coastal Plain to elevations of several hundred feet. While little drilling has as yet been done in the vicinity of the necks, and the geological structure is therefore somewhat speculative, the general cross-section is presumed to be somewhat as in figure 12. At the base of the upheavals and surrounding them in close proximity the Tamasopo limestone and overlying formations form pockets or places of catchment where large deposits of oil have accumulated. In the Tamasopo limestone and the San Felipe beds these oil deposits were presumably concentrated from surrounding portions of the same strata, owing to the upheavals mentioned; possibly with the assistance of heat.

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[61] E. G. Norton: Origin of the Louisiana and east Texas salines. Am. Inst. Mining Engrs., Bull. No. 97, Jan., 1915, p. 93.

[62] E. T. Dumble: The occurrences of petroleum in eastern Mexico as contrasted with those in Texas and Louisiana. Fuel Oil Journal, Oct., 1915, p. 86.

[63] V. R. Garfias: The effect of igneous intrusions on the accumulation of oil in northeastern Mexico. Jour. Geol., vol. 20, no. 7, Oct.-Nov., 1912, p. 666.

The presence of the oil accumulations surrounding the plugs is sometimes, although not always, evinced by large seepages of oil. Some cases are known where the lower beds actually reach the surface and a true quaquaversal structure exists. Whether this is common has been doubted,[64] but it is certain that definite doming does exist surrounding some of the plugs. At any rate it is a fact that where the plugs exist pockets of oil have accumulated, and the conical plugs themselves may be considered as quaquaversal structures.

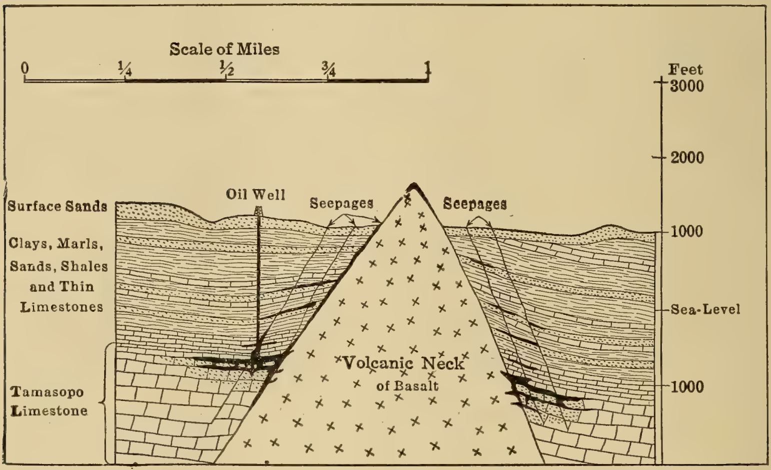

FIGURE 12.—*Hypothetical Cross-section of a volcanic Plug in the Coastal Plain of Mexico*

Showing occurrence of petroleum according to Subclasses IV (*d*), V (*d*), and Class VII

It would appear that large deposits of oil might be expected in the vicinity of such intrusive masses in all cases where porous sands are overlaid by a suitable cover to prevent the escape of oil. Where the impervious covering or cap rock is unusually thick or without fractures, seepages may be absent, although they exist in the vicinity of most of the basaltic cones. One case was seen where asphaltic oil was flowing down the side of a cone from a breccia included in the basalt 50 to 60 feet above the surrounding plain. It is supposed that this oil entered the basalt through fissures, which extend into the plug from the oil sand, and that its passage through the basalt was caused by the great pressure under which it existed.

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[64] E. De Golyer: The effect of igneous intrusions on the accumulation of oil in the Tampico-Tuxpam region, Mexico. Econ. Geol., Nov.-Dec., 1915.

Volcanic necks of basalt are scattered at wide intervals throughout the Gulf Coastal Plain of Mexico. The greatest center of volcanic activity was the Otontepec and Tantima Mountains, several thousand feet in height, in the State of Vera Cruz. The volcanic activity seems to have become less at increasing distances from these mountains and decreased almost entirely before reaching the Rio Grande far to the north. The majority of the plugs are only a few hundred feet in height and some of them less than 100 feet, and it is probable that many exist which never reached the surface. The geological relations of the basalt renders it undoubtedly of more recent origin than the Coastal Plain sediments; and although frequently no disturbance can be discovered surrounding the plugs, there is no doubt that such disturbances do exist and that Subclass IV(*d*) is a necessity.

No igneous rock has been definitely proven in saline domes; but Captain Lucas thought he had igneous rock beneath the salt in a 3,300-foot well at Belle Isle, Louisiana.[65] That the volcanic neck type is presumably more common than is yet known is evinced by the fact that on the southern edge of the Transylvanian basin in Hungary, where saline domes are the prevailing type, arranged in linear series similar to those of Louisiana, is one prominent instance where a plug of basalt rises above the plain instead of the saline dome which is due at the particular point.

Subclass IV(e)—Perforated saline domes.—In Transylvania and Roumania the saline dome type of structure has frequently reached an exaggerated phase, owing to the fact that the dome-shaped salt masses have reached the surface of the earth, and that the surrounding strata have been compressed outward to such an extent that they stand vertical, or even are overturned in a narrow belt surrounding the dome. In Roumania large oil fields are found in such structures, which were originally described by Professor Mrazek as "diapir structure" or perforated domes. While this type may exist in America, it is not known to the writer as oil-bearing. In New Brunswick certain gypsum deposits appear to be of similar structure and probable origin, but are not supposed to contain oil.

Perforated domes may be considered as a class intermediate between

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[65] A. F. Lucas: Trans. Am. Inst. Min. Engrs., vol. 48, p. 693.

Subclasses IV (*c*) and IV (*d*). So far as we know, the oil-bearing domes of this type are limited to Roumania; but others appear in Transylvania which appear not to have been adequately tested. Figure 13 is an illustration of a perforated dome in Roumania after Bosworth.[66]

It is probable that some of the saline domes of the Gulf Coastal Plain of the United States may be of the perforated type; but if so little, if any, oil has been found in them and none has been found in the perforated domes of Transylvania. In Roumania oil occurs in association with perforated domes, among other places in the Baicoi field, as illustrated by Thompson.[67]

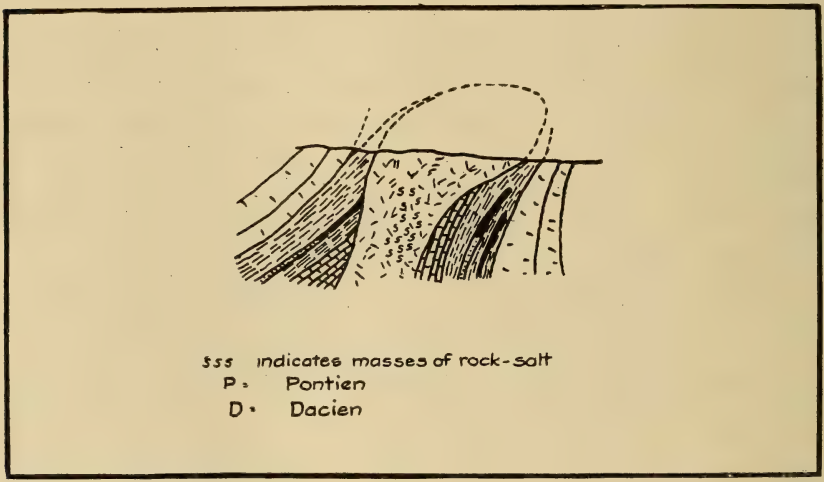

FIGURE 13.—*Cross-section of Oil Field at Baicoi, Roumania*

Illustrating occurrence of oil according to Subclass IV (*e*). After Bosworth. Petroleum Review, March 23, 1912

Features common to all types of quaquaversal structure.—Although many differences exist between oil fields of Types IV (*a*), (*b*), (*c*), (*d*), and (*e*), these subclasses are similar in many respects. First, in order to hold oil, they must combine all of the several factors which appear essential in every field, namely: (1) a porous stratum, to hold the oil; (2) an impervious cover, to keep it from escaping, and (3) some sort of geological structure by which the oil, gas, and water may have been separated and the oil concentrated in one locality. In anticlinal and synclinal fields the structure or folding of the beds has acted as factor (3); hence we may expect to find gas on the up-dip side or nearest the crest of the dome, water on the outskirts and oil between, generally at the point of greatest change in rate of dip. This relation appears true in all fields, though in some saline dome fields the dip is so steep that water is pumped in large quantities from the same well as the oil. Moreover, gas is not such an important commercial factor in quaquaversal structure as in certain other types of oil fields. An evidence that the structure constitutes the concentrating factor is brought from the Louisiana and Texas fields, where hundreds of wells have been drilled away from the saline domes, with a result that no oil was found. In this class of fields, as in the monoclinal and anticlinal types, the oil seems to have been widely disseminated in the porous strata and ultimately accumulated at favorable points where the regularity of the dip is locally interrupted, or where held in by water, gas, dikes, faults, or by pinching out of the porous strata.

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[66] Pet. Review, March 23, 1912, p. 172.

[67] A. Beeby Thompson: Trans. Instn. Min. and Met., vol. 20, 1910-1911, p. 223, fig. 40.

CLASS V—CONTACT OF SEDIMENTARY AND IGNEOUS ROCKS

Subclass V(a)—Contact of sedimentaries with volcanic plugs.—The importance of this class is attested by the fact that the close association of seepages with the volcanic plugs of Cerro de la Pez and Cerro de la Dicha was the direct cause of the discovery of the Ebano field, the first in Mexico. A large number of seepages also occur surrounding volcanic plugs at Cerros Chapapote and Las Borrachas near Juan Felipe; Cerros Palma Real and Cacalote near Potrero de Llano; Cerro Pelon near Solis; Mata de Chapapote, at Caracol and Apachiltepec on Tlacolula, and many other places.

The principal function of igneous intrusion in the accumulation of oil is believed by De Golyer[68] to have been the formation of channels through which the oil has been able to migrate into the overlying formations and even to reach the surface. A secondary and relatively unimportant function of intrusion is believed to have been the formation by brecciation and metamorphism of reservoirs capable of containing oil.

Subclass V(b)—Contact of sedimentaries with dikes.—Many of the Mexican seepages occur along dikes of basaltic rock in the Tertiary sediments. The Tampalachi seepage near Panuco, Mexico, occurs on a concealed dike. Other instances of seepages along dikes occur at Tamijuin, Acala, Chapapote in the San Jose de las Rusias hacienda, and one mile southeast of Cervantes. This last is illustrated in figure 14.

Subclass V(c)—Contact of sedimentaries with intrusive beds or laccoliths.—Few cases are known with certainty where oil occurs below intrusive beds or laccoliths, but figure 15 shows how the type is believed by some to occur in Mexico, and undoubtedly exists in Cuba. The Furbero field is reported by De Golyer[69] to overlie and underlie an altered laccolith of gabbro in the Mendez shales, which are there baked and broken. Thompson[70] supposes that the structure of the field of the island of Tcheleken, in the Caspian Sea, may be due to an underlying laccolith.

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[68] E. De Golyer: Econ. Geol., vol. 10, 1915, p. 661.

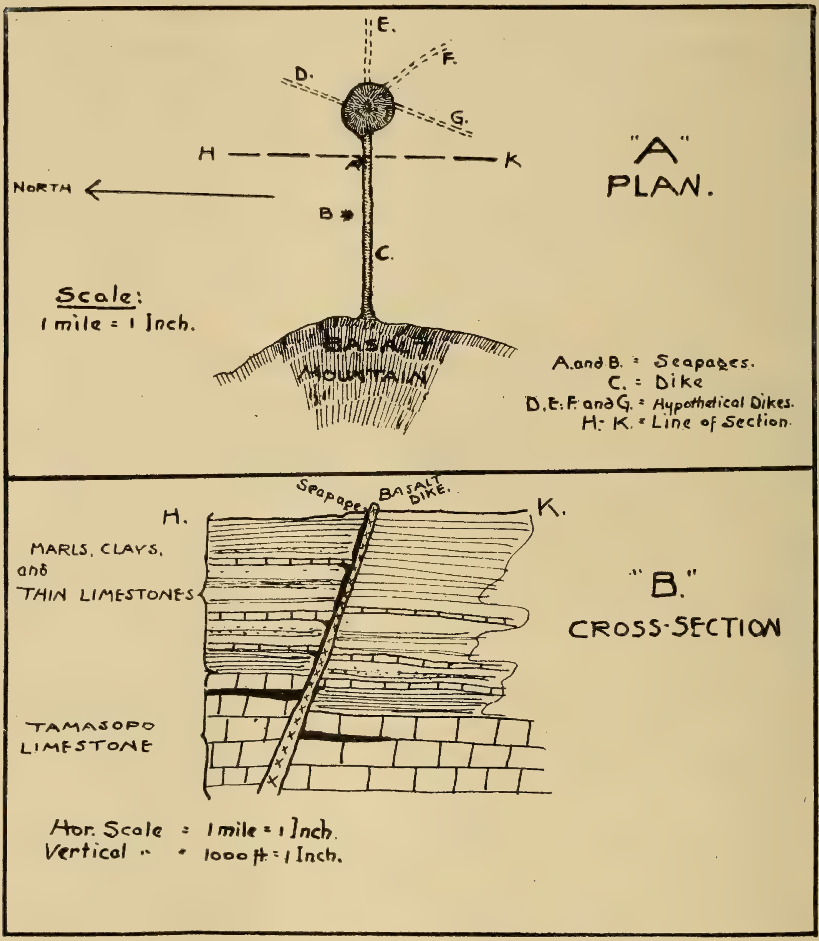
E.
F.
D.
G.
H
K
"A"
PLAN.
NORTH
A
B
C.
Scale:
1 mile = 1 Inch.
BASALT MOUNTAIN
A. and B. = Seapages.
C. = Dike
D., E., F. and G. = Hypothetical Dikes.
H.- K. = Line of Section.
Seapage.
BASALT DIKE.
H.
K.
MARLS, CLAYS, and THIN LIMESTONES
"B."
CROSS-SECTION
TAMASOPO LIMESTONE
Hor. Scale = 1 mile = 1 Inch.
Vertical " = 1000 ft = 1 Inch.

FIGURE 14.—*Plan and Cross-section of a Dike in Mexico*
Showing occurrence of oil according to Subclass V (*b*)

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[69] Econ. Geol., vol. 10, 1915, p. 653.

[70] Instn. of Min. and Met., vol. 20, 1910-1911, p. 230.

Subclass V(d)—Contact of sedimentaries with older igneous rocks.—While there are no positively known occurrences of oil according to this type, gas does exist in small quantities in this way in the provinces of Quebec and Ontario and in northern New York State, where it is under great pressure. So far as the writer has been able to learn from his informants, it is contained in the lower zone of the Potsdam sandstone, of arkose structure, resting directly on the underlying granite or gneiss.

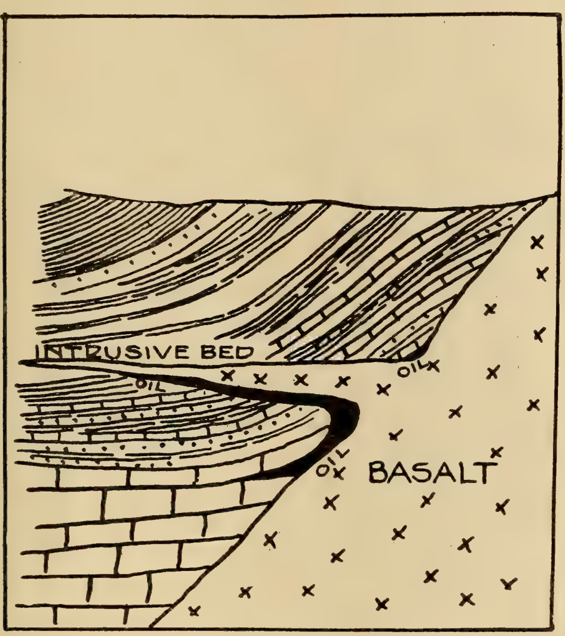

FIGURE 15.—*Hypothetical Cross-section of an intrusive Bed in the Coastal Plain of Mexico*

Illustrating occurrence of oil according to Subclass V (*c*)

CLASS VI—STRATA DIPPING UNCONFORMABLY AWAY FROM AN OLD SHORELINE

A good example of oil in an unconformity on a monocline is brought by Thompson[71] from the Maikop field of Russia, where inclined strata of Upper Oligocene and Lower Neocene age, dipping 7 to 10 degrees, rest unconformably on an overlap Cretaceous strata, as shown in figure 16. The unconformity has sealed up the upper end of the Neocene sands. The structural position of some pools in the vicinity of the Arbuckle and Wichita Mountains, in southern Oklahoma, may be similar.

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[71] Trans. Instn. Min. and Met., vol. 20, 1910-1911, p. 229.

CLASS VII—CREVICES OF IGNEOUS ROCKS

Petroleum and solid bitumen have been noticed by various observers in traps, basalts, and other igneous rocks. An interesting instance was mentioned by Logan[72] in a greenstone dike at Tar Point, Gaspe, in the Province of Quebec. Another unpublished occurrence of oil in igneous rock from Colorado, contributed by Dr. David T. Day, refers to a boulder of vesicular basalt in which the vesicles were filled with oil. In order to prove whether the oil had filtered in from exterior sources, a fragment was boiled with benzol until no more oil could be extracted, and the basalt still contained much oil. It was shown, however, that the cavities had been sealed by a secondary deposit of carbonate of lime, and that by removing this the oil could all be extracted and the basalt left intact. Thus the external origin of oil was deemed possible.

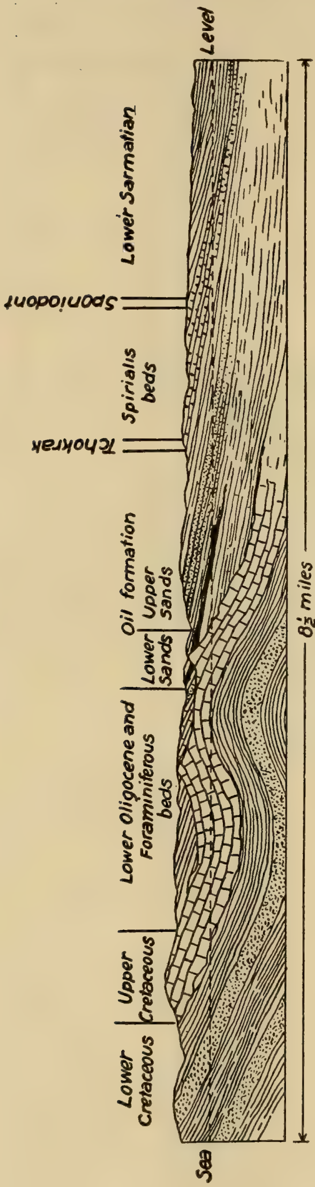
Level
Lower Sarmatian
Spaniodont
Spirialis beds
Tchokrak
Oil formation
Upper Sands
Lower Sands
Lower Oligocene and Foraminiferous beds
Upper Cretaceous
Lower Cretaceous
Sea
8½ miles

FIGURE 16.—*Section through Shirvanskaya Wells, Maikop Field, Russia*

Showing occurrence of oil according to Class VI. After Thompson

In the vicinity of Binny Craig, Scotland, a volcanic neck or pipe was encountered in an oil-shale working. This dike consists of trap and contains cavities in which mineral wax, pitch, or paraffine was found.[73] These instances are not, however, in the opinion of the present writer, due to igneous origin of the oil, but to the intrusion of the volcanic rock from below into the sedimentary formations which contained the oil, and consequently the volcanic rock must have absorbed large quantities of bitumen. Moreover, in Mexico many crevices exist in the volcanic necks, and these are sufficient to allow oil to enter from the surrounding Tertiary and Cretaceous formations and thus pass up to the surface.

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[72] Sir William Logan: Geology of Canada, 1863, pp. 400-789.

[73] Henry M. Cadell: Oil-shale holdings of the Lothians. Trans. Inst. Min. Engrs., vol. 22, pp. 347-353.

Rateau mentions[74] an instance at Roczk, Galicia, where a trachitic rock is impregnated with petroleum. A similar report comes from Prof. Arthur Lakes,[75] who describes dikes of injected volcanic origin, more or less saturated with petroleum, near Pagosa Springs, in Archuleta County, Colorado. The petroleum here is also associated with hot sulphur water. De Golyer[76] mentions probable examples of oil seepages from dike fissures at Cerros de la Pez and de la Dicha, at Ebano, Mexico. The best example known to the writer is from the side of Cerro de Chapapote, between Tepezintla and Pierre Labrada, Mexico, where oil can be seen seeping out of a conspicuous basalt plug from about 60 feet above its base. Washburne[77] mentions the occurrence of small amounts of oil in porous basalt on the Johnson Ranch, on the North Fork of Siuslaw River, western Lane County, Oregon.

A somewhat different type of occurrence is found in granite and associated crystalline rocks on Copper Mountain, in northeastern Fremont County, Wyoming, according to Trumbull.[78] For many years asphalt, oil tar, or "brea," as it is frequently called, was gathered for fuel from points on the granite mountain. The geology has been worked out in detail by Darton,[79] who found that Copper Mountain is a dome over the granite core of which stratified rocks were at one time present, having been removed by erosion. The brea and deposits of heavy oil have accumulated in hollows in the upper part of the mountain, and oil has been encountered in shafts and tunnels high up in the granite. The oil was originally accumulated in the Ember sandstone of Permian age which overlay the dome, and when the faulting occurred some of it settled into the crevices of the granite as low as the water level. The downward stratigraphic migration is supposed to have been as much as 2,000 feet, but the direction of migration is described as probably lateral during tilting of the rocks to form the dome.

CLASS VIII—CREVICES OF SEDIMENTARY ROCKS

The Florence field of Colorado is shown by Washburne[80] to be due to joint cracks and fissures in shale. The oil does not follow any particular beds or series of beds and the oil zone contains no sandstone or other porous beds. Washburne's evidence on this matter, which seemed decisive, was as follows:

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[74] M. A. Rateau: Annales des Mines, 8th ser., vol. 11, p. 152.

[75] F. H. Oliphant: Mineral resources of the United States for 1910. U. S. Geol. Survey (1902), p. 561.

[76] E. De Golyer: Econ. Geol., vol. 10, 1915, p. 655.

[77] C. W. Washburne: U. S. Geol. Survey Bull. 590.

[78] L. W. Trumbull: Bull. No. 1, Scientific Series of the State of Wyoming, Geologist's office, 1916, pp. 5-16.

[79] N. H. Darton: Prof. Paper 51, U. S. Geol. Survey.

[80] C. W. Washburne: Bull. 381, U. S. Geol. Survey, 1910, pp. 521-523.

1. Correspondence in direction of major joints with alignment of interfering wells.
2. Lack of productivity of some wells situated only a few feet from productive wells.
3. Occasional ruining of a deep well by tapping the source of pressure by a neighboring shallow well.
4. Draining of many wells by adjacent wells of much greater depth.
5. Marked increase of maximum pressure with depth.
6. Dissimilar pressure in adjacent wells of the same depth.
7. "Crevices" reported by drillers.
8. Disappearance of large quantities of water poured into the wells.
9. Reported dropping of drilling tools.

In northeastern Ohio, southern Texas, and in some localities in Wyoming small oil and gas wells are frequently obtained in shales outside of known domes, anticlines, or other structures. This is generally called "shale oil," or "crevice oil," to distinguish it from the normal structural type. The shale oil is believed by many to be indigenous to the beds in which it is found.

CLASS IX—OIL ASSOCIATED WITH CLOSED FAULTS

General discussion.—The known examples of this class consist of some pools in the Los Angeles field and some in the Lompoc field in California, described by Arnold. In these cases the highly inclined oil sands are cut off abruptly below ground by a fault, thus sealing in the oil and gas and preventing their escape to the surface. To explain the probability that such occurrences are more frequent than is known, it may be worth while to mention that oil springs frequently occur along fault-lines in British Columbia, in Gaspé in Quebec, in Wyoming, and in Mexico. This type is illustrated in figures 17 and 18.

Subclass IX(a)—Oil on the upthrow side.—Definite examples of oil on the upthrow side of faults are frequent in Oklahoma and they may exist elsewhere. No localities are mentioned on account of professional connections, which demand secrecy.

Subclass IX(b)—Oil on the downthrow side.—A good example of oil along the downthrow side of faults in the Coalinga field in California is illustrated in figure 17, after Arnold. Numerous other cases doubtless exist.

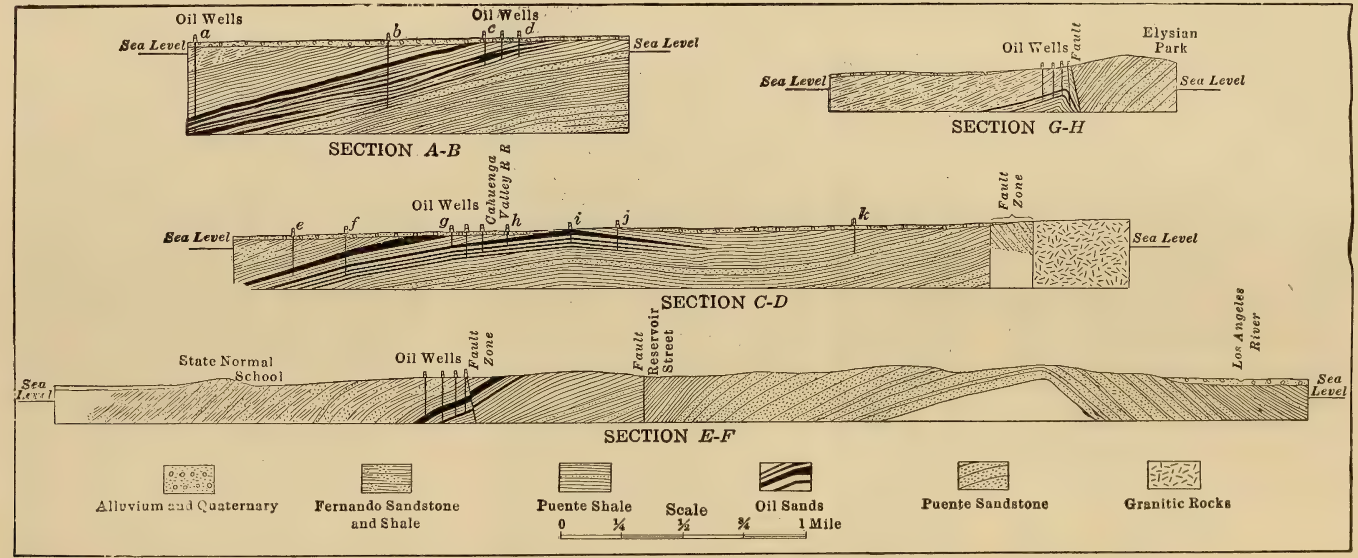
Oil Wells
a
b
Oil Wells
c
d
Sea Level
Sea Level
SECTION A-B
Oil Wells
Fault
Elysian Park
Sea Level
Sea Level
SECTION G-H
Oil Wells
Cahuenga Valley R R
e
f
g
h
i
j
k
Fault Zone
Sea Level
Sea Level
SECTION C-D
Sea Level
State Normal School
Oil Wells
Fault Zone
Fault
Reservoir Street
Los Angeles River
Sea Level
SECTION E-F
Alluvium and Quaternary
Fernando Sandstone and Shale
Puente Shale
Scale
0
¼
½
¾
1 Mile
Oil Sands
Puente Sandstone
Granitic Rocks

FIGURE 17.—*Geologic Sections through the Los Angeles Oil Fields, California*

After Eldridge and Arnold, Bulletin 309, U. S. Geological Survey, plate 20, showing occurrence of oil according to Subclasses II (*b*), II (*e*), and IX (*b*)

Oil on both sides of the fault.—In many of the Oklahoma fields oil is found both on the upthrow and downthrow sides. In the Bibi-Eibat field of Russia oil occurs on both sides of normal faults which cut the crest of the anticline, as shown by D. Golubiatnikoff.[81] According to Thompson,[82] the faults in the Bibi-Eibat field exercise an important influence on the production of the wells. The faults are inclined and wells are drilled to strike them at great depths. In some cases the production of wells on one side of the fault was much greater than on the other.

Subclass IX(c)—Oil along overthrust faults.—Examples of oil fields along overthrust faults are brought from Roumania, where they are well known. A cross-section of the Bustenari field, after Bosworth,[83] is here shown in figure 19. A minor instance is in the Pincher Creek pool of southern Alberta. One of the best published examples is described by Arnold and Johnson[84] in the McKittrick field in California (figure 20), where the shales of the Monterey and Santa Margarita formations of Middle Miocene age are supposed to have been overthrust along a low-angled plane, on top of the McKittrick gravels, clays, and oil sand of Upper Miocene age.

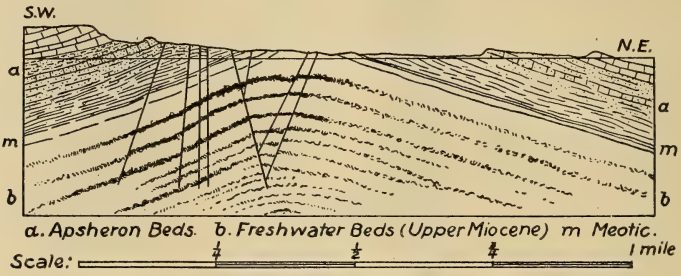
S.W.
N.E.
a
m
b
a
m
b
a. Apsheron Beds. b. Freshwater Beds (Upper Miocene) m Meotic.
Scale:
¼
½
¾
1 mile

FIGURE 18.—*Section through Bibi-Eibat Field of Baku, Russia*
Showing occurrence of oil on both sides of faults, Subclasses IX (*a*) and IX (*b*), and also coming in Subclass II (*b*). After Thompson

CLASS X—OIL SANDS SEALED IN BY BITUMINOUS DEPOSITS AT OUTCROP

This class, apparently having been first postulated by the writer, has since been referred to by other writers. The Pitch Lakes of Trinidad and Venezuela are believed to be the best known examples. In some of the California fields[85] the outcrop of the sands is believed to be closed by brea. Some of the oil found near the vein of grahamite, described by

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[81] D. Golubiatnikoff: Bull. Geol. Com., St. Petersburg, vol. 23, 1904.

[82] A. Beeby Thompson: Petroleum mining and oil-field development, New York and London, 1910, p. 57.

[83] T. O. Bosworth: Pet. Review, March 23, 1912, p. 172.

[84] Ralph Arnold and Harry R. Johnson: Bull. 406, U. S. Geol. Survey, 1910, pp. 97-99.

[85] Arnold and Johnson: Loc. cit., pl. v.

White[86] at Ritchie Mines, West Virginia, may belong to this class, although these deposits are also dependent in their original accumulation on anticlinal and synclinal structures of Subclass II(*b*). The source of the West Virginia grahamite dike is believed to have been the Cairo oil sand, which lies at a depth of about 1,300 feet from the surface; and there is no doubt that either now or at an earlier period certain of the oil was held in by the grahamite.

The source of the albertite dike in Albert County, New Brunswick, is believed to have been oil intruded from petroliferous strata and which fills a large vertical fissure in the fine-grained Albert shales[87] of Lower Carboniferous or Devonian age. The fissure was in places as much as 17 feet wide and was mined to a depth of 1,300 feet. The albertite also fills many branch veins in the wall rock. Many dikes of grahamite of similar origin exist in Stephens, Pushmataha, and other counties in southern Oklahoma. The uintaite (gilsonite) of Utah has been shown by Eldridge to occupy a fractured zone in the central Uinta synclinal basin. Many parallel vertical gilsonite veins exist from one-sixteenth of an inch to 18 feet in width and from a few hundred yards to 8 or 10 miles in length, paralleling the mountains which border the basin. Oil will not be found in proximity to all these dikes, as some of the bitumens show by their

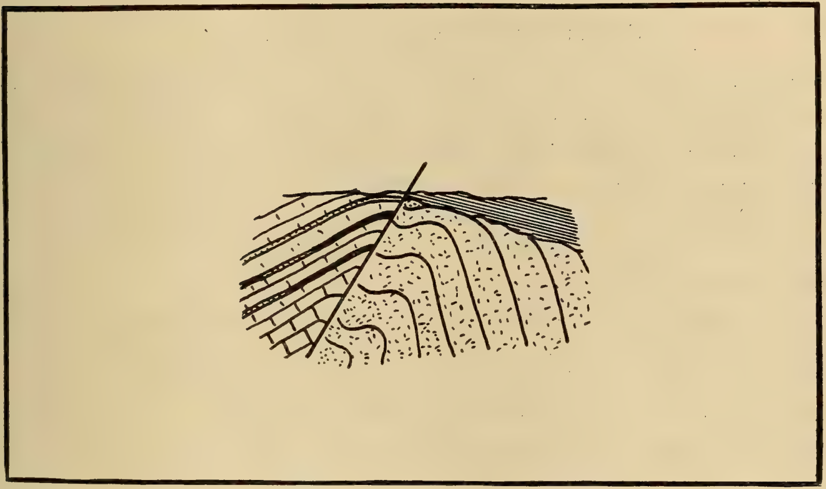

FIGURE 19.—*Cross-section of the Bustenari Field, Roumania*

After Bosworth, Petroleum Review, March 23, 1912, showing occurrence on overthrust fault according to Subclass IX (*c*) composition that the locality has suffered too great metamorphism, but some of the deposits constitute indications of oil.

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[86] I. C. White: Bull. Geol. Soc. Am., vol. 19, 1899, pp. 277-284.

[87] L. W. Bailey and R. W. Ells: Geol. Survey Canada, 1876-1877, p. 354 et seq.

To illustrate the importance of bitumen dikes as indications of the former presence of petroleum and natural gas, it may be said that the grahamite dike of West Virginia is in the center of one of the greatest oil and gas regions in the world; that the albertite of New Brunswick is only a few miles from the Stony Creek gas field; that the grahamite dikes of Oklahoma are within a few miles of known oil fields, and that the uintaite dikes of Utah lead in a general direction toward oil, which is found across the boundary in Colorado.

OTHER CONDITIONS THAN STRUCTURE

The mistake must not be made of supposing that any one of the types of structure is a positive indication of an oil field. Many other conditions hold true, as we all know. After the structure has been determined, it is necessary to learn (1) whether suitable sands with impervious covers exist, (2) whether they are dry or wet, (3) whether there is any probable source of oil or gas, and (4) whether the region shows evidence of too great metamorphism, etcetera.

Some persons have intimated that the structural classification is inadequate and hence of no value. To this criticism its propounder will merely reply that it has proved of inestimable value to him and to many other persons inside and outside of the profession. It is, of course, far from perfect or complete; yet some sort of a classification is needed, and nothing has yet been suggested which comes near being a substitute. That proposed by Johnson and Huntley,[88] in which the structures are arranged in only four main classes, may offer some advantage by its apparent simplicity, but no other formal classification is known.

There are, however, several particulars in which fields appear to depart from the ordinary structural principles, namely:

1. As pointed out many times in structural treatises, the determining factor in the distribution of gas, oil, and water in any pool is not the general plane of the bed, but the undulation of the surfaces constituting the roof and floor of the reservoirs.

2. Lenticularity of the sands. In a strict sense of the word, of course all oil sands are lenticular, though some extend continuously hundreds of miles with little change in character. An example of this persistency is the Clinton sand of Ohio.

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[88] Principles of oil and gas production, 1916, p. 63.

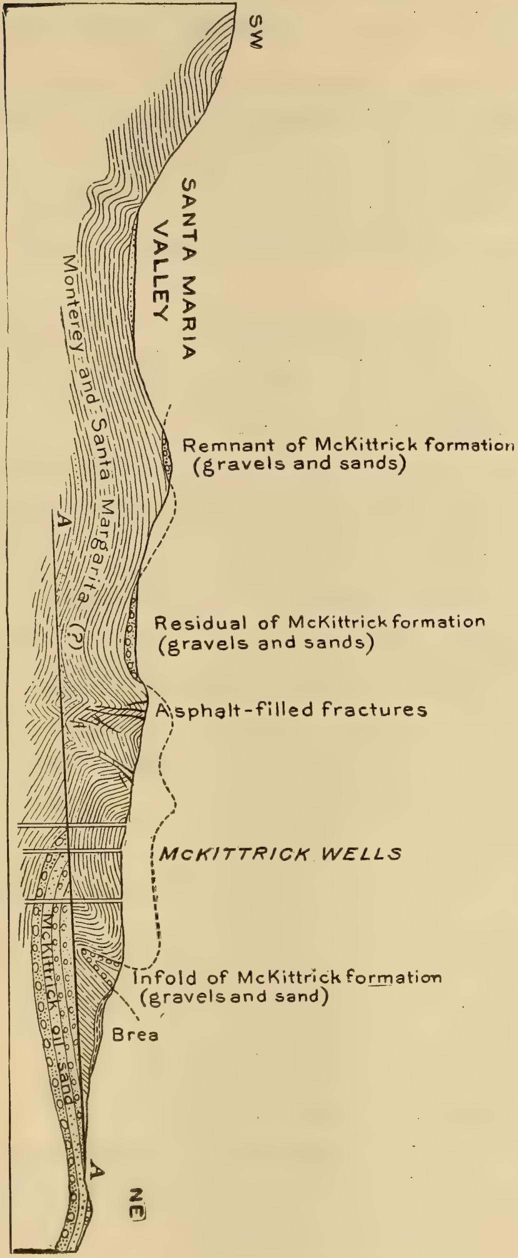
SW
SANTA MARIA VALLEY
Monterey and Santa Margarita (?)
A
Remnant of McKittrick formation (gravels and sands)
Residual of McKittrick formation (gravels and sands)
Asphalt-filled fractures
McKITTRICK WELLS
Infold of McKittrick formation (gravels and sand)
Brea
McKittrick oil sand
A
NE

FIGURE 20.—*Cross-section in McKittrick Field in California* Illustrating occurrence of oil below overthrust fault. After Arnold and Anderson

3. No porous stratum is consistent throughout, but varies greatly in its cementation, size, and arrangement of particles and therefore of pore space.

4. The common non-parallelism of different sets of strata in any field. This is what we technically call the convergence of the strata. The structure of the productive stratum itself must be considered independently of the configuration of structure in any surface formation.

5. Dryness of certain sands.

6. Extreme saturation of certain sands.

Relation between Structure and Topography

A much closer relation exists in some fields between geological structure and topography than is commonly understood, but this coincidence must be accepted with reservation.

Arnold and Johnson state[89] that in the McKittrick-Sunset region of California a very close relation exists between topography and structure, the preservation of the forms being "due in part to the aridity of the climate, which has prevented the obliteration of the main features, although not always of the minor folds and in part to the recency of some of the processes which have affected the folding and faulting." As examples are mentioned Pyramid Hills, Lost Hills, Elk Hills, Buena Vista Hills, Antelope Plains, and Syncline Hill. The topographic effect of faulting in that region is described as even more striking than that of the folding, as exemplified by Palo Prieto Pass, the Elkhorn Scarp, etcetera.

A similar close topographic relation exists in places in Oklahoma and Texas; in Wyoming it is very manifest, and it can be distinguished to some extent in Pennsylvania, Mexico, Kansas, and Canada.

Causes of Failure of geological Work in Search of Oil

The common causes of failure are as follows:

(1) Inadequate investigations, due to
    (*a*) Lack of funds allotted to the work.
    (*b*) Lack of sufficient time.
    (*c*) Lack of engineering training on the part of the geologist.
    (*d*) Lack of geological training on the part of engineers.
    (*e*) Lack of distinction between "reconnaissances" and "detailed examinations."

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[89] Loc. cit., p. 93.

- (*f*) Personal carelessness of the geologist.
- (*g*) Jumping to conclusions.
- (*h*) Undue optimism.
- (*i*) Faulty instructions.

(2) Locations not on sufficiently high portions of the dome or anticline, due to

- (*a*) Fear of getting gas.
- (*b*) Inadequate investigations.
- (*c*) Improbability of securing desired leases.

(3) Abnormal sand conditions.
(4) Absence of knowledge regarding salt water.
(5) Unconformities.
(6) "Convergence," or lack of parallelism of the sands not being understood.
(7) Inclined axes of certain anticlines.
(8) Sharpness of certain anticlines.
(9) Rising and plunging axes.
(10) Lack of suitable sands.
(11) Lack of suitable cover.
(12) Lack of source of supply.
(13) Past leakage, or imperfect understanding of relation between magnitude of folding and age or metamorphism of the formations.
(14) Lack of judgment on the part of the geologist.

It is the intention of the writer to take up in a later report these causes of failure, analyze them, and endeavor to derive some conclusion which will eliminate the failure, so far as possible, in geological studies of oil properties.

Structural "Habits" Peculiar to Individual Fields

In any stated field, oil and gas exist after certain methods of "habit," which seem to prevail generally throughout that field. This is because, while the substances adhere in their relations to structural principles, there are modifying conditions which cause certain peculiarities to run entirely through the field. For instance, the central Ohio fields owe their monoclinal structure to the Cincinnati uplift; they are too far from the Allegheny Mountains to be subject to the prominent folds produced in Pennsylvania and West Virginia, but they all show certain *tendencies* toward anticlinal structure, as exhibited by monoclinal noses and ravines and terraces and by changes in rate of dip in short distances.

On the other hand, in the Oklahoma and Kansas fields, on a great monocline between the Ozark Mountains and the Great Plains geosyncline, there are numerous domes and anticlines, due to some sort of pressure forces aside from those which elevated the mountains on the east or west of the fields.

Substance of a geological Examination

Considering the last few pages, we must, in closing, call attention to the fact that while geological structure is the most important factor in any examination for finding oil or gas, all the other factors must be given due weight in forming our conclusions; and, above all, we must use our judgment in digesting the field data. It is important, after finding the structure, to proceed in the following manner:

1. Make as accurate a structure-contour map as available data will permit.
2. With the help of "convergence maps," make a separate geological and well map for every individual sand.
3. Before making any recommendations, consider carefully the question of local peculiarities of the structures—water conditions, number, character, parallelism and continuity of the sands, character of overlying beds, possible source of supply, metamorphism, and "structural habits" for the particular group of fields.

By such an appraisal of the characteristics of the region, it will not be difficult to form some conclusion of the probabilities of the prospective field.

Conclusion

In a scientific study of any oil field for the purpose of determining its possibilities, it is necessary for the expert to distinguish the features which it has in common with other fields from those in which it differs from them, and by a process of comparison and inference, based on the detailed observations and calculations, to draw his conclusions as to whether or not the locality is favorable for petroleum.

It is probable that oil will continue to be discovered in types of structures not enumerated here, and from time to time further additions and subdivisions of the classification must be made. We can record in the present classification only what is now actually known or inferred.

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GENERAL CONDITIONS OF THE PETROLEUM INDUSTRY AND THE WORLD'S FUTURE SUPPLY[1]

BY RALPH ARNOLD

(Presented before the Society December 28, 1916)

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[1] This paper is one of a series composing a "Symposium on the Geology of Petroleum." See this volume, p. 156.

Manuscript received by the Secretary of the Society December 26, 1916.

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Introduction

Petroleum has assumed such a position in the industrial world in the last few years as to place it in the first group of minerals essential to civilization, and as its discovery and recovery are so obviously problems of applied geology, it is peculiarly fitting that the Geological Society of America should devote especial attention to it at this time.

It is the purpose of this paper, which is intended to open the discussion, to briefly outline the present conditions surrounding the oil industry and the problems confronting it, especially the most important problem, that of future supply.

General Conditions surrounding the Petroleum Industry

PRESENT WORLD'S OUTPUT

The world's production of crude petroleum in 1915 was 427,695,347 barrels; the 281,104,104 barrels of this produced in the United States was worth an average of about 80 cents per barrel, or a total of $224,883,283; the balance of the world's production was worth at least an average of $1 per barrel, so that the total value of the entire world's production for that year was approximately $371,474,526. The value of the derivatives of this oil could not have been less than a billion to two billion dollars.

The relative rank of oil producers of the countries of the world with respect to one another is shown by the following table compiled by the United States Geological Survey:

World's production of crude petroleum in 1915 and total yield since 1857

Country	Quantity, 1915			Quantity, 1857–1915		
	Barrels of 42 gallons	Metric tons	Per cent of total	Barrels of 42 gallons	Metric tons	Per cent of total
United States	*a* 281,104,104	37,480,547	65.72	*a* 3,616,561,244	482,208,266	60.09
Russia	68,548,062	9,353,077	16.03	1,690,781,907	222,984,256	28.09
Mexico	32,910,508	4,388,068	7.69	123,270,377	16,420,008	2.05
Dutch East Indies *b*	12,386,808	1,710,445	2.90	148,999,921	20,087,939	2.48
Roumania	12,029,913	1,673,145	2.81	130,012,387	17,477,878	2.16
India	8,202,674	1,093,690	1.92	81,592,385	10,878,984	1.36
Galicia	4,158,899	578,388	.98	136,032,500	18,918,364	2.26
Japan and Formosa	3,118,464	415,785	.73	30,169,622	4,022,606	.50
Peru	2,487,251	331,633	.58	16,794,223	2,239,229	.28
Germany	995,764	*c* 140,000	.23	13,961,333	1,875,974	.23
Trinidad	*c* 750,000	100,000	.18	2,819,430	375,924	.05
Argentina	516,120	75,900	.12	1,033,121	151,693	.02
Egypt	221,768	29,569	.05	1,308,496	174,466	.02
Canada	215,464	28,729	.05	23,709,074	3,161,210	.39
Italy	39,548	*c* 5,500	.01	842,020	119,279	.01
Other	*c* 10,000	1,333	.01	372,000	49,600	.01
	427,695,347	57,405,809	100.00	6,018,260,040	801,145,676	100.00

a Marketed production. *b* Includes British Borneo. *c* Estimated.

GENERAL CONDITIONS AFFECTING THE INDUSTRY

Like practically all others, at the present moment, the petroleum industry is affected by the abnormal conditions of the great war. Whereas the demand is great, the means for meeting this demand are restricted by the lack or high price of material for development purposes, lack of transportation facilities, and the isolation or destruction of several important oil fields. The need of transportation facilities has tended to increase the price of oil where it is consumed and to decrease the price where it is produced. An excessive demand having been created for the lighter derivatives of petroleum, such as gasoline and distillates, a very considerable part of the energy now being devoted to the industry has for its object the conversion of heavy oil into light, and many ingenious methods are being invented to accomplish this result. The demand has also started almost frantic efforts, not only in this country, but abroad, to find new oil fields. Normal conditions can come only after a termination of the war.

FACTORS GOVERNING THE PETROLEUM INDUSTRY

Laying aside for the moment the unusual and considering the normal phases of the industry, we find that it is governed by factors numerous and complicated. They may be divided roughly into two groups, the one including natural factors, the other artificial. The geologist has to do largely with the first group, the financier and the business man with the second, the petroleum technologist with both. Since this is primarily a geologic meeting, the writer will confine the discussion largely to the geologic factors. Among these may be mentioned origin of oil; rock pressure or pressure under which the oil and gas exist in their underground reservoir, and which affects migration and accumulation; viscosity and other chemical and physical properties of the oil; the thickness, extent, porosity, and structure of the reservoir rock, and the relation of the oil to other substances, such as water and gas, which are concomitant with the oil in most oil fields. In the group of artificial factors, or those having to do with the recovery and use of the oil, might be mentioned the price of oil and gas, which is usually the dominant artificial factor, and such others as depth of wells, time required to complete wells, distance separating wells, character and physical condition of wells, pumps and other equipment, improvements in methods of development and recovery, water complications, discovery of new fields, distance of fields from markets, transportation facilities, relative cost of production of oil as compared with the cost in other fields and with the cost of other commodities with which oil comes into competition, personnel of the operators, relation of the government to the industry, etcetera.

Natural Factors and their related Problems

ORIGIN

Probably the most enticing subject from a scientific viewpoint, as well as the most unsatisfactory, in connection with petroleum is that of its origin. Many theories have been advanced to account for it, but as yet no absolute proof has been brought forward in substantiation of any particular one. The most commonly accepted theory is that petroleum is derived through more or less tedious processes from organic remains, either animal or vegetable, or both, laid down under water, usually in intimate association with limestone or fine shale-forming sediments. The alteration of this material to crude oil is accomplished through the agency of bacteria and types of distillation and filtration under moderate temperatures. Another problem related to that of origin is the one having to do with the character of the oil, whether it be of asphalt or paraffin base. Both problems involve a consideration of complex factors.

MIGRATION AND ACCUMULATION

The problems of migration and accumulation of oil should tempt the lithologist as well as the geophysicist and the structural geologist. It is well known that water influences the migration and accumulation of liquid hydrocarbons, and that the structure is also an important factor; but it is only recently that the great influence of even minor changes in the lithology of the containing strata has been recognized. Other factors affecting migration and accumulation are the character of the oil and rock pressure, either hydrostatic, hydraulic, or due to gas. Naturally all of these factors are intimately related, and one can no more isolate a single factor for study than he can expect to study geology intelligently without a knowledge of physics and chemistry.

CHEMICAL AND PHYSICAL PROPERTIES

The study of the chemical and physical properties of petroleum, including as it does the innumerable problems of the refining industry, is a science in itself. Its importance may well be imagined from a brief survey of the following, among other of the characteristics of petroleum. Crude oil is a mixture of a number of chemical compounds consisting of about 84 to 86 per cent of carbon, 11.5 to 14.5 per cent of hydrogen, and minor quantities of nitrogen, oxygen, and sulphur. It is usually a fluid at ordinary temperature; in its wider sense the term is made to include natural gas and the solids, such as asphaltum and paraffin. It is usually lighter than water, its specific gravity varying from about 1.000 to 0.750. Its color in reflected light ranges from light amber through green to black; in transmitted light, amber through deep red to black. The heavier oils are very viscous, the lighter ones much less so. The calorific value of oil ranges from 18,000 to 20,000 B. T. U.'s, or about one and one-half times that of good bituminous coal. The flash point and fire point of crude petroleums vary greatly, the lighter oils, containing much gas, usually being dangerous to handle on account of low flash point, while the heavier oils are hard to kindle.

CONDITIONS NECESSARY FOR COMMERCIAL DEPOSITS OF OIL

Without going into details, it may be said that to have a commercial deposit of oil three things are essential: First, an adequate source of supply in the form of organic sediments, such as shales or limestones; second, a suitable reservoir in the shape of porous beds or zones covered by or inclosed in impervious formations; and, third, the occurrence of the reservoir near enough to the surface to permit of the recovery of the oil on a paying basis. In nature it is not at all unusual to have two of the conditions fulfilled, such, for instance, as the presence of organic shales near the surface—this is common throughout practically all of the areas of sedimentary rocks—but to find reservoir conditions in proper association with an adequate supply near the surface is a rare coincidence.

WORLD'S SUPPLY LIMITED

Because petroleum is a natural product and is sometimes produced in prodigal quantities in certain fields, people commonly have the notion that there is an unlimited supply of oil in the earth's crust. It is true that petroleum or associated hydrocarbons occur almost universally, especially in regions of sedimentary rocks; but it is likewise true that petroleum in commercial quantities is confined to a limited number of restricted areas throughout the world. As indicative of the relatively small area yielding commercial quantities of petroleum, it might be mentioned that the total area of the United States is 3,025,640 square miles; the proven oil-producing area 4,109 square miles, or 13 one-hundredths of one per cent of the entire area. When it is considered that the United States is the most extensively developed of the important oil-producing countries, it can be readily understood that commercial deposits of oil are rare.

WHY PETROLEUM DEPOSITS ARE RARE

A study of the chemical and physical properties of petroleum—its origin, migration, and accumulation—makes clear why its distribution is so wide, but its segregation in commercial deposits so restricted. In the first place, because of its origin it is confined almost exclusively to a certain group of rocks, namely, sedimentary; secondly, it is a liquid at ordinary temperatures, susceptible to evaporation when exposed to the air, and never a stable compound, even when confined. Slow distillation is always taking place in crude petroleum, generating gas which tends to expand and cause migration and dissipation of the oil. In most deposits the tendency to migrate because of the generation of gas is augmented by hydrostatic pressure. Oil is therefore not a stationary, but a migratory, substance. Third, a natural oil reservoir once emptied will never fill again for generations, commonly speaking.

The World's Future Supply

In discussing the relative importance of the various countries of the world as producers of petroleum, the question of probable future productiveness must often be considered apart from that of their past and present yield, for in some cases the country, like the United States, is at its zenith or past, while other countries, like Persia or Colombia, with little or no production at present, may offer evidence of later becoming important producers.

According to this table, it is seen that nearly three-fourths of the world's supply is now coming from North America, including Mexico, and that the bulk of the remainder comes from Russia. The United States has produced about 60 per cent of the total production to date, while Russia has produced only about half as much, or a little over 29 per cent. As regards future production, it is probably safe to say that Russia, or possibly even Mexico, will outstrip the United States. This condition is true because of the early and intensive development of petroleum in the United States, due to the proximity of the fields to markets, the character of our citizens who went into the business, and the attitude of our Government. The last two factors are always important ones and ones that will be in the future, as they have been in the past, the determining ones in many instances. These same two factors are also the dominant ones, almost universally, when it comes to conservation of oil, and it is the balance between the forces of exploitation and those of conservation that determines the efficiency with which petroleum, as well as other natural resources, is produced and utilized.

In discussing the present and future sources of the world's supply of petroleum, the countries will be taken up in geographic order, beginning with North America. The future possibilities, obviously the most interesting to this audience, will receive the most attention.

North America

CANADA

All three of the countries in North America, namely, the Dominion of Canada, the United States, and Mexico, are petroleum-producing.

The Canadian fields, though among the oldest in the world, never have been of very great importance. The production at present is confined to Ontario, where 200,000 barrels of high-grade oil are produced annually. The oil comes from beds of Ordovician to Carboniferous age. Indications of petroleum are found in some of the other provinces. Extensive areas in western Canada offer indications suggesting the presence of oil in commercial quantities, and it is believed that the future will see the Dominion take its place as an important producer of petroleum.

UNITED STATES

The oil fields of the United States are so well known as to need little discussion before this audience. They are classified usually as Appalachian, Lima-Indiana, Illinois, Mid-Continent, Gulf, Rocky Mountain, and California fields. Their proved area includes over 4,100 square miles, with prospective territory of, possibly, 1,000 square miles. The production for 1915 was about 280,000,000 barrels. The probable reserve supply is about 5,500,000,000 barrels. The oil is found in formations ranging in age from the Ordovician to the latest Tertiary. The quality ranges from the asphalt-base oils of California and Texas to the lighter paraffin-base oils of the eastern part of the United States. At the present rate of consumption, the estimated supply would last only about 20 years; however, as the total production of the United States will gradually decrease from year to year from now on, it is believed the total available supply will spread out over a period from 50 to 75 years, with a gradually increasing price for the oil as the production drops.

Before the free natural petroleum in the earth is exhausted, the oil shales of Colorado, Utah, California, and other States will have begun to be utilized as a source of petroleum; also artificial oil made from animal and vegetable waste will probably be available to take its place.

MEXICO

The known oil fields of Mexico are located along the Gulf Coastal Plain and include about 20 fields, covering areas of over 20,000 square miles. A very rough estimate of the proved area is 25 square miles, with a prospective area of 500 to 1,000 square miles. The largest wells in the world are found in these fields. They tap the porous and cavernous Cretaceous limestones, and one at least has been known to yield over 250,000 barrels per day. A total production of over 40,000,000 barrels has been yielded by one well. The production of the country was 34,000,000 barrels in 1915, and bids fair to far surpass this point when political conditions in Mexico shall have become more stable and the war in Europe permits of the utilization of more marine transportation facilities. We may safely look on Mexico as one of the greatest sources of the oil supply of the future.

Central America

Little is known of the oil possibilities of Central America. Surface evidences of petroleum are found in nearly all of the countries, but from the information available it does not seem probable that any very commercially important fields will ever be developed in them.

West India Islands

With the exception of Trinidad, the islands of the West Indian group offer little evidence of becoming important commercial producers of petroleum. The production of Trinidad in 1915 was about 750,000 barrels. The oil ranges from high to low grade, the low-grade oil predominating.

South America

PERU

Although indications of oil are found in practically every country in South America, the countries in which commercial quantities of oil are now being produced, or which offer evidence of a commercial yield in the future, are Colombia, Venezuela, Peru, Argentina, and Bolivia.

Little development has been done outside of Peru, which was the first country in South America in which oil was produced on a commercial scale. The petroliferous areas in this country are situated along the northwestern coast and are known as the Zorritos, Lobitos, and Negritos fields. Of the total area of 5,000 square miles included in the oil belts, about 200 square miles can be said to be either proven or highly probable, while about 100 square miles more has oil possibilities. The oil comes from Lower Tertiary beds and is of high quality. It seems likely that this country will increase in production for several years to come, but that it never will yield more than 5,000,000 to 10,000,000 barrels yearly.

ARGENTINA

Argentina produces some oil from a field on the coast at Comodoro Rivadavia. The producing area is limited and the product heavy grade. Along the eastern base of the Andes, in western Argentina, are areas offering evidence of a commercial production of a good grade of oil. These areas, though far from transportation, will doubtless be tested at some future date and may yield important quantities of oil.

COLOMBIA

Little development has been carried on in Colombia, but superficial evidence leads to the belief that out of a possible oil territory of something like 600 square miles a fairly important commercial production may be developed in time.

VENEZUELA

Like Colombia, Venezuela is still in an untested state as to its future possibilities.

ECUADOR

Ecuador has produced small quantities of oil for a number of years, but does not offer evidence of ever becoming highly productive.

EUROPE

GERMANY

The important oil deposits of Europe as at present developed are found in Germany, Austria, Roumania, and Russia. Indications of petroleum are found in practically all of the other countries, and Italy yields commercial quantities of oil in restricted areas of the interior.

Germany, which produced less than a million barrels yearly before the commencement of the war, has been a fairly consistent producer for years. It is probable that abnormal, intensive drilling has been carried on since the outbreak of the war, and that production may now be somewhat above that of normal years. Germany has no important future as an oil producer, however.

AUSTRIA

The oil fields of Austria and Roumania form a belt along the northeastern and eastern flanks of the Carpathian Mountains. The Austrian fields are confined to Galicia, where commercial quantities have been yielded for many years. The oil is principally of a light, refining grade, paraffin base, and comes from rocks of Eocene and Oligocene age in simple anticlines along the base of the mountains, or sometimes from complex structures in the same region.

Galicia obtained a maximum production in 1909, when it produced 15,000,000 barrels of oil; it produced about 4,000,000 barrels in 1915, and although there are many untested areas offering evidence of a good production, it is probable that Galicia never again will produce as much as it has in the last few years.

ROUMANIA

The production of Roumania is now about at its zenith, 12,000,000 to 13,000,000 barrels having been produced yearly during the past three years. Intensive development may maintain its production for a short time, but as a factor in the future Roumania cannot expect to exceed its present relative importance of fourth or fifth in the list of world's producers.

RUSSIA

The word "Russia" fills the mind with pictures of unusual and great things, and it is true to its traditions as regards oil. The producing fields are confined principally to the northeastern shore of the Black Sea, the western shore of the Caspian Sea, and the flanks of the Caucasus Mountains, lying between the two. Among the important fields are those of Baku and Grosny. Practically all of the oil comes from the Lower or Middle Tertiary, usually along anticlines, though productive areas with complex structure are not rare. Practically all grades of oil are found in the Russian fields. Russia is a country in which the government regulations have tended to retard rather than accelerate development, and were it not for the fact that nature has been so generous with her as regards oil she would not occupy the second place among the world's producers as she does now. Russia reached her apex of production in 1901, when she produced over 85,000,000 barrels. In 1915 she produced about 68,000,000 barrels. Such large areas, both in European and Asiatic Russia, yield unmistakable evidence of oil in large quantities, that it is to this country, among those of Europe and Asia, the future must look for a supply. Many obstacles, both governmental and natural, will have to be overcome to recover the oil; but demand will force the overcoming of these, and for many years in the future Russia can be counted on to hold second rank, and eventually first, among the world's producers.

Asia

GENERAL DISTRIBUTION

The oil fields of Asia are largely potential. Turkey, Persia, Arabia, and India now yield oil in commercial quantities, the last named standing sixth in order of importance in the world.

TURKEY

Mesopotamia and the Tigris and Euphrates valleys yield some oil, and it is possible that some commercially important fields ultimately may be opened up in these districts; but it does not seem probable that for some time to come Turkey will contribute materially to the world's supply.

PERSIA

The principal deposits of Persia are confined to the southwestern part of the country, although important deposits are known on the Caspian shore, south of Baku. The oil comes from Tertiary beds and usually is of a high quality. As only the more accessible portions have been developed as yet, and as much highly probable territory remains untested, it seems probable that this country eventually will become an important factor in Asiatic oil production.

ARABIA

The oil fields in Arabia suggest the possibility of commercial deposits, the principal ones lying near the Persian Gulf, the Red Sea, and Yemen province.

INDIA

The principal oil fields of India are found in Burma and Assam. The fields have been operated for years and produce important quantities of high-grade refining oil. Numerous districts in Burma and Assam show promise, and this country doubtless will become more important as a source of oil as time goes on.

CHINA

China has not yet produced oil in important commercial quantities, and although considerable prospecting has been done within its borders, the evidence now available indicates that probably it never will play a very important part in the production of oil.

EAST INDIES AND ADJACENT ISLANDS

DUTCH EAST INDIES

The Dutch East India islands of Borneo, Sumatra, and Java are among the most important sources of oil in the world. They are also among the most interesting geologically, as the oil fields are marked by some wonderful surface phenomena, such as mud volcanoes and great oil seepages. The oil-bearing strata are of Tertiary age. The oil is mostly of a high-grade refining type, but the production of individual wells usually is not large. Those familiar with the islands claim that there are hundreds of square miles of oil land yet undeveloped, so that it seems probable that this source, so important at the present time, will remain so for many years.

The Celebes, Tunor, and Ceram islands also offer evidence of commercial production.

PHILIPPINE ISLANDS

Indications of high-grade petroleum are found at several localities in the Philippines and some prospecting has been done in a small way. Capital stands ready today to go in and make a thorough test of the favorable localities as soon as a stable government is established in the islands. Prospectors are willing to take a chance with the none too good natural conditions in these islands, but wisely refrain from placing their investments under the control of the vacillating island government which has existed for the past four years. It is not deemed probable that these islands ever will become very important as a world supply.

JAPAN

Japan has come to the front within the last few years as a small producer of petroleum of medium grade. The deposits are of Tertiary age and extend from the Pacific coast of Totomi to the west side of north Japan. The deposits, though not extensive, are still of such importance as to suggest a much larger annual production ultimately than the 3,000,000 barrels produced in 1915.

AUSTRALIA, NEW ZEALAND, NEW GUINEA

Indications of petroleum are found in southeastern Australia, at several places in New Zealand, and in west central New Guinea; but up to date no commercial deposits of oil have been opened up in these great British possessions, nor does it seem likely that this quarter of the globe ever will yield important quantities of oil.

Africa

The only production of oil in commercial quantities in Africa comes from Egypt, where Tertiary beds near the Red Sea yield a good production of fair-grade oil. It seems probable that further development in the Egyptian fields will result in a greatly increased production over that yielded to date.

Algeria offers favorable indications in the Miocene formations, and other parts of Africa which either have been tested or which yield indications of production are Nigeria, Belgian Congo, Gold Coast, and the island of Madagascar. So little is known of these areas that any prediction as to their future possibilities would be extremely hazardous. It is reasonable to suppose that somewhere within the great area of sedimentary rocks of this continent commercial quantities of oil exist and eventually will be exploited.

Summary

Summarizing the data contained in the foregoing paragraphs, it is seen that the countries which have attained their maximum production, and are either about to decline or have already started to decline, are the United States, Italy, Galicia, and Germany. Canada attained a maximum production in 1900 and Russia in 1901; but owing to the possibilities of new fields yet to be opened, it seems probable that both these countries will soon start to increase their production, with the probabilities strong that Canada, at least, will some day pass her former banner year. All of the other countries may be credited with a constantly increasing production. The total world's production has been increasing gradually since 1857, and it seems likely that after the close of the war the greatly increased demand for oil will result in increasing the world's output beyond the 427,000,000 barrels yielded in 1915 and possibly beyond the half billion mark. The demand probably will be such as to cause this great output to be maintained for as long as the fields of the world can supply it. Disregarding Africa, which is an unknown, but probably not highly important, factor in the situation, it is the writer's belief that the high point in production for the entire world will occur within the next ten years.

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APPALACHIAN OIL FIELD[1]

BY MYRON L. FULLER

(Presented before the Society December 28, 1916)

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[1] This paper is one of a series composing a "Symposium on the Geology of Petroleum." See this volume, p. 156.

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INTRODUCTION

The Appalachian oil field is unquestionably the best known of any of the American fields, not only for the reason that it is the oldest, but because, being the first, it attracted the attention of geologists and oil men to a degree never attained by any of the fields subsequently opened. Its literature is voluminous and its published historical and scientific records are more complete than those of any other field in the United States. The structure has been worked out over broad areas with great detail and refinement, especially in the northern and central sections of the field, by the National and State geological surveys, and probably few, if any, of what may be called the major dynamic structures have escaped recognition.

Nevertheless, much still remains to be accomplished in unraveling the minor, but by no means unimportant, details of structure and in reaching a better understanding of other factors governing the occurrence of petroleum and natural gas. The Appalachian field is as yet by no means approaching exhaustion, and no symposium on the oil resources of the country would be complete without a consideration of its history, output, and structure from the standpoint of its bearing on future production. It is

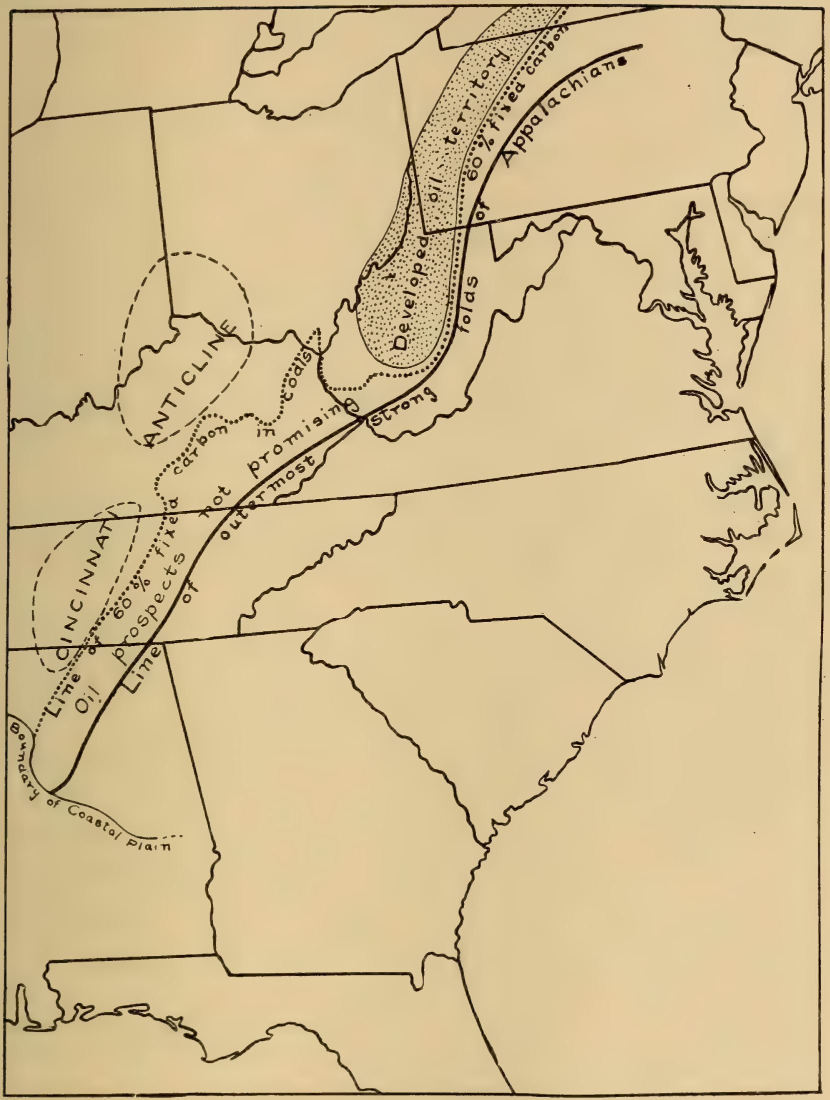
Developed oil territory
60% fixed carbon
Line of outermost strong folds of Appalachians
Line of 60% fixed carbon in coals
Oil Prospects not promising
CINCINNATI ANTICLINE
Boundary of Coastal Plain

FIGURE 1.—*Map of Appalachian Region*

Showing relation of developed oil field to the 60 per cent line of fixed carbon in coals. With a few minor local exceptions, neither oil nor gas has been found east of the western face of the outermost strong fold of the Appalachians. Between this face and the 60 per cent carbon line there is considerable gas in the north (smaller amounts in the south) and an occasional small oil pool. The main developed oil field lies west of the 60 per cent carbon line. That it does not extend farther west and south is because of the less favorable stratigraphic and structural conditions. There are, however, numerous small oil pools in this belt in Ohio, Kentucky, and Tennessee.

with the object of presenting such a review and prediction that the present paper has been prepared.

HISTORICAL SUMMARY

EARLY MENTION

There is a romance attached to the Appalachian oil field in the minds of most geologists and oil men that is associated with no other American field. The overwhelming rush of the oil from the ground, the terrific pressure of the escaping gas, the running streams of the dark, oily liquid, and the flaming pools and oil-covered rivers, coming, as they did, at a time before the public mind had been satiated with the new wonders of the telephone, electric light, electric power, X-ray, wireless telegraphy, and the mysteries of radium, created an impression that is still vivid after the lapse of more than half a century.

The oil seepages near Cuba, Allegany County, New York, appear to have the distinction of being the first in North America to be mentioned, reference to them being found in a letter of a Franciscan missionary as early as July 19, 1627.[2]

About 1753 an account and map of the oil springs near what is now Oil Creek, Pennsylvania, was published by Peter Kaln, who had visited the region in 1748.[3] At this time these springs were almost certainly known to the garrison at Fort Du Quesne (Pittsburgh), as well as to the officers and soldiers of the Colonial and British forces who penetrated the region during the French and Indian War a few years later. The oil and gas springs of West Virginia were also well known before the Revolution, for George Washington preempted in 1775 the "burning springs," nine miles below Charleston, on the Kanawha, as a part of the lands granted him by Virginia as recompense for his military services. The Oil Creek springs of Pennsylvania were again mentioned by Gen. Benjamin Lincoln, who described the use of "Barbados tar" for medicinal purposes by his troops in the Revolution. The medicinal fame of the oil had also spread abroad, being mentioned in German literature in 1789.

By the beginning of the nineteenth century petroleum had become well known as an antidote for rheumatism, burns, sprains, etcetera, chiefly under the name of Seneca oil, from Seneca Lake, Alleghany County, New York. The oil came from a pool some 18 feet in diameter, from the surface of which it was scraped. It was subsequently purified by heating and straining through flannel. Although free at the source, the oil sold as high as 50 cents for a small vial in the coast cities in 1833.[4]

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[2] G. Sagard: "Histoire du Canada et Voyage des Missionaires Récollets," 1636.
[3] "En resa til Norra Amerika." Stockholm, 1753-1761.

By this time it had also come to be used in lamps in the vicinity of its source, usually after infiltration through charcoal.[5] Its use for lighting the City of Pittsburgh had already been advocated in 1828, and its value as a lubricant had been recognized.

EARLY WELLS

The first drilled well to obtain oil appears to have been a 2½-inch boring put down for brine by the Ruffner brothers at Salt Lick, near the Kanawha River of West Virginia, in 1806. A depth of 58 feet was attained by the spring-pole method, a hollow sycamore being used for casing through quicksand to the rock at 17 feet. A large number of brine wells followed in the Kanawha district of West Virginia and on the Muskingum and Duck Creek in Ohio, nearly all of which afforded some petroleum. Although the yield from some of the wells is estimated to have reached from 25 to 50 barrels a day, the oil was of no value at the time, and was allowed to flow away over the top of the brine cisterns into the streams, giving the nickname of "Old Greasy" to the Kanawha.[6]

The first flowing well, or gusher, of note which the writer has seen mentioned is the so-called "American Well," on Little Rennox Creek, Cumberland County, Kentucky. While seeking brine in 1829, this well encountered a streak of pure oil giving "incredible" quantities in intermittent discharges at two to three-minute intervals. The outflow has been estimated at 1,000 barrels a day; but although it continued to yield oil by flow or to pumps for over 30 years, the well was never utilized except to a negligible extent as a source of medicinal oil.[7]

By 1845 the decline of the whale-oil industry and the rise in price of the sperm oil, which for several generations had supplied the lamps of the country, had centered attention on other means of illumination, and in 1846 Abraham Gesner is reported to have distilled oil from coal. Patents were shortly afterward granted to Gesner and many others, and plants sprang up rapidly, both in America and in Europe, especially in Scotland. Even the sacred precincts of the whale industry at New Bedford were invaded, and by 1859 there were about fifty companies engaged in the distillation of oil from coal or shale in the United States. The price commonly ranged from 60 to 70 cents per gallon.

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[4] Benj. Silliman, Jr.: Am. Jour. Sci., vol. i, no. 23, 1833, p. 97.

[5] S. P. Hildreth: Am. Jour. Sci., vol. i, no. 24, 1833, p. 63.

[6] J. P. Hale: "Resources and Industries of West Virginia," prepared for the State Centennial Board, 1876, chapter xii.

[7] Niles Register (3), vol. xiii, p. 4; Burkesville Courier, Oct. 11, 1876.

Amidst this manufacturing enthusiasm the production of natural petroleum was overlooked by all but a few. By 1859, however, serious efforts to obtain natural oil were being made. A shaft was sunk to a depth of 220 feet, at a cost of $20,000, near Tarentum, Pennsylvania, obtaining considerable oil, and a good trade in oil and lamps, the latter sold with the oil, was worked up in New York.

OPENING OF THE FIRST AMERICAN OIL POOL

On August 28, 1859, Col. E. L. Drake, Superintendent of the Seneca Oil Company, organized by George H. Bissel, struck a "crevice" at Titusville, Pennsylvania, at a depth of 69 feet. The following day the well was found full of oil and was pumped at an initial rate of 25 barrels a day.

It was not a large well, its yield being but a small fraction of that of the "American Well" of Kentucky, and smaller than many of the Kanawha brine wells, but the public had by this time become educated to the use, or at least to a knowledge of the value, of the oils distilled from coals and shales, and the country was ready and the time ripe for the development of natural petroleum. Other wells followed the Drake well in rapid succession, and the great oil boom was on.

Pool after pool was opened. A flowing well, the first in Pennsylvania, was struck near Rouseville during the following summer, while 1861 saw many gushers, several of them yielding from 3,000 to 4,000 barrels a day. Oil ran like water, covering the ground, collecting in pools, or flowing over the surface as streams. Ignited, the pools and streams became lakes and rivers of fire. From $20 a barrel in the summer of 1859, the price of oil dropped to 10 cents at the end of 1861. From that time on, however, the price mounted steadily for several years, culminating at $10 in January, 1865.

LATER DEVELOPMENTS IN PENNSYLVANIA AND NEW YORK

The year 1860 saw the opening of the Petroleum Center, Rynd Farm, Rouseville, Oil City, and Tidioute pools in Venango County. In 1861, the Tarr Farm pool, with its big gushers, and the Franklin pool, both in Venango County, were opened. Pithole, in the same county, was opened in 1865. The development of the "lower country," including Butler, Armstrong, and Clarion counties, began in 1868.

Gradually the developments were extended in all directions, first to the north and later to the south. The Bradford pool was opened in 1875, and the Warren in 1876. The extension of operations into New York came about 1880. Active drilling began in southeastern Ohio about the same time. From 1878, though fewer big pools were opened, the production mounted upward, with a temporary setback from 1883 to 1886, until 1891, when the output of Pennsylvania and New York culminated in the yield of 33,000,000 barrels per annum. The late developments have been mainly southwest of Pittsburgh, with small pools to the east and northeast in rocks of steeper dips.

DEVELOPMENT OF OIL IN WEST VIRGINIA

Following the boom inaugurated by the bringing in of the Drake well at Titusville, Pennsylvania, in 1859, an old brine well at Burning Springs, West Virginia, was reopened and gave 50 barrels a day, while the following year the Lewellyn well, 100 feet deep, started at 1,000 barrels a day and soon increased to 2,000 barrels. Confederate raiders destroyed the wells in 1863, and drilling was not actively resumed until 1865, when the success of wells at White Oaks led to the development of some excellent territory.

The early wells were mostly along the Burning Springs-Eureka anticline, extending from Burning Springs, in Wirt County, northward to Eureka, Pleasants County, on the Ohio, where the lower rocks were brought within the limits of spring-pole drilling. The opening of the other districts was delayed nearly 30 years, owing to the comparative great depth to the oil sands and the inadequacy of the prevailing methods when applied to caving rocks.

Although production was continuous from 1859 to 1888, the volume never exceeded 200,000 barrels per annum, and was usually under 150,000. In 1889, however, owing to improved methods and a better understanding of the geology, the production leaped in a few months to half a million barrels, and continued upward until 1900, when it passed the Pennsylvania-New York output, which had declined from 33,000,000 barrels in 1891 to 14,559,000 barrels in 1900, reaching a total of over 16,000,000 barrels. Since then the decline has been slow, paralleling closely that of the two States mentioned.

DEVELOPMENT OF OIL IN EASTERN OHIO

Boring for brine became active in 1806 and following years along the Muskingum Valley, etcetera, on the flanks of the prolongation of the Burning Springs-Eureka anticline across the Ohio River and north of the salt district of West Virginia; but, as in the latter State, the oil was a nuisance and no use was made of it at the time. The wells were, however, reopened and new ones drilled, following the Pennsylvania oil excitement in 1859-1860, and some oil obtained. The production remained very low for many years and only reached 50,000 barrels per annum in 1883-1884. After 1885, following the revived activity in Pennsylvania and West Virginia, new pools were opened along the eastern border of the State west of the pools of the States named, including the Macksburg, Sistersville, and Eureka districts, and production mounted rapidly to several million barrels per annum. For the last 15 years the annual production has maintained itself at a surprisingly constant level, mainly be-4,800,000 barrels. The later Clinton sand developments do not belong properly to the Appalachian field.

DEVELOPMENT OF OIL IN KENTUCKY

Beginning about 1806-1807, wells were bored for salt at several points along Big Sandy River and its tributaries, many of which yielded enough petroleum to be troublesome. One, known as the Beatty well, bored for brine about 1819, in Wayne County, was abandoned for 40 years on account of petroleum, but was reopened about 1860, and produced oil for many years. The American well, sunk in 1829, estimated to produce 1,000 barrels a day at the start, was unutilized except for medicinal oils.

Much prospecting has been done, especially in Pulaski, Wayne, Russell, Clinton, Wolf, Cumberland, and Barren counties, but the pools have been small. The maximum production was 1,217,000 barrels in 1905, largely from Barren, Wayne, and Wolf counties, after which date the output declined to 500,000 barrels in 1914. In 1915 and 1916 there was renewed activity in drilling and some promising pools were opened up.

DEVELOPMENT OF OIL IN TENNESSEE

Oil was known in the brine wells in the first decade of the nineteenth century. The oil of one well on the line between Clay and Pickett counties flowed out on the river in 1820, giving a considerable conflagration when ignited. A large flow from another near-by salt well was reported in 1837.

Owing to the Civil War, prospecting did not actively begin until 1865-1866, when Northerners who had noticed the oil seepages, etcetera, while with the Federal armies returned and started drilling. Prospecting has continued intermittently ever since, but only a few small pools have been developed, chiefly along the northeastern edge of the Tennessee dome of the Cincinnati anticline, in Overton and Pickett counties. Production on a commercial scale was reported from 1893 to 1907, but the output has never exceeded a few thousand barrels per annum.

DEVELOPMENT OF OIL IN ALABAMA

Following the beginning of the petroleum excitement in Pennsylvania many wells were drilled in Alabama, mainly near the gas springs or oil seepages which had long been known along the outcrop of the Carboniferous beds near the southern termination of the Appalachian Mountains. Some oil and gas were obtained, but not enough to encourage development, and little further testing was done for over a quarter of a century. In 1889, however, several deep wells were sunk to the Trenton, obtaining oil in two horizons. The yield was stated to have been 25 barrels per day; no development followed, and test drilling has never since been actively pushed, although there were some small developments about 1912. Alabama has never ranked as a producing State.

Influence of Geology on Development of Oil

Geology has played a most important part in the development of the Appalachian oil field. While it is true that the first wells were located solely on the basis of seepages, and that the discovery of all of the earlier pools resulted from purely wildcat drilling, the later developments have been far more rapid, much less expensive, and the production greater and more prolonged than would have been the case had the operations not been directed largely by geology.

In the earlier days a large proportion of the drillers and operators were absolutely convinced that a fixed relation existed between the occurrence of oil and the minor features of surface topography, and hundreds of wells were located upon hills of a certain type, in valleys of a particular depth or width, or beneath conglomerate ledges of a particular appearance which happened to possess a physical resemblance to locations that had been found productive elsewhere. In the Appalachian district there was seldom, if ever, any scientific basis for such locations, although there is a distinct relation between the general topography and the major anticlines on the east. Elsewhere, however, as in certain parts of Oklahoma, domes may sometimes be locally recognized by topography, although it is never safe to drill without geological verification.

As soon as the developments became moderately extensive it was noted by operators that the Pennsylvania pools were commonly of elongated outline, with nearly straight axes of fixed magnetic bearing. This gave rise to the "degree lines," which for some years were the chief guides in new developments. The bearings north 22½°, 30°, 35°, and 45° east were among the most popular, each having many adherents. Although the drillers were long unaware of their relation, such lines were governed strictly by the local geology and usually coincided with the strike of the beds or the axes of the folds. Where founded on sufficient data, they were naturally a great help in drilling; but, unfortunately, they were often applied to districts other than those from which they were derived. The use of a north $22\frac{1}{2}°$ east line in a region where strike was north 45° east meant failure from the start. Nevertheless, some drillers continued to place implicit faith in them for many years. Even within a few years the management of one of the largest Pennsylvania companies conducted its explorations in one field on degree lines running in all directions of the compass, the sole basis being the positions of scattering wells located miles apart. Yet this was in a country where the structure was absolutely clear and many years after the anticlinal principle had been firmly established.

The first recognition of the anticlinal principle in literature appears to have been by T. Sterry Hunt in 1861;[8] but the same conclusions as to the relation of oil to anticlines were reached independently, and almost simultaneously, by Prof. E. B. Andrews,[9] of Marietta, Ohio. The publication of these views made no impression on oil men, if indeed they ever heard of them, and prospecting was continued for the next 20 years on the basis of degree lines, divining devices, or mere impressions.

Although the relation of oil to anticlines continued to be pointed out from time to time by Newberry, Stevenson, and others, it was not until the beginning of the great boom in natural gas that the attention of operators and scientists was finally riveted on the anticlinal principle. Mr. William A. Earseman, an operator who had noted the coincidence of the great Pennsylvania gas wells with the anticlinal axes as drawn on the maps by the Second Geological Survey, suggested a geological investigation to Mr. J. J. Vandergrift, then President of the Forest Oil Company. Dr. I. C. White was engaged to make this investigation, and in June, 1883, he visited all the big gas wells of the Appalachian field. From these studies he found that "every one of them was situated on or near the crown of an anticlinal axis, while wells that had been bored in the synclines on either side furnished little or no gas."[10]

The correctness of Doctor White's conclusions were verified within the next few years by the location of the Grapeville, Washington, and other great gas pools. Guided by the same principles, Doctor White pointed out for Pittsburgh parties in 1884—long before the drill finally located them—the probable locations of what have since proved to be the great oil pools of West Virginia. The results were especially noticeable in the years following 1888. The importance of Doctor White's work can hardly be overestimated. While not the originator of the anticlinal theory, he may be considered as the one who first proved it by the successful location of wells. Since that day structural terraces and a score of subordinate features have been found to play an important part in the distribution of oil, but the anticlinal principle underlies practically all of them.

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[8] Montreal Gazette, March 1, 1861; Canadian Naturalist, vol. 6, 1861, pp. 241-255.

[9] Am. Jour. Sci., vol. ii, no. 32, July, 1861, p. 85 (article dated May 20, 1861).

[10] Science, June 26, 1885.

At first only a few companies were sufficiently far-sighted and progressive to break away from the traditional methods, but gradually, one by one, they adopted the anticlinal principle as a guide to their operations. Today few companies of prominence disregard geology. Capital for development can be obtained only on a favorable report by a geologist. Geologists are found in every field. Even in an old and declining field like the Appalachian their services are still of great value, and the life of more than one company, or oil or gas pool, has been prolonged through their help after production under old methods had reached a standstill.

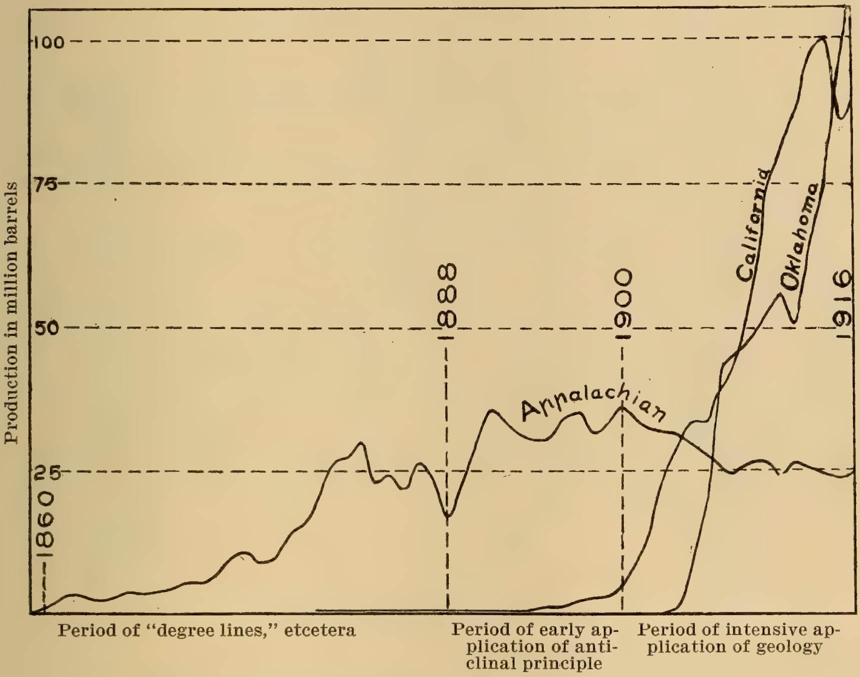

FIGURE 2.—*Curves showing Relation of Oil Production to Geology*

While, because of other factors involved, it is difficult to state quantitatively the effect of geology on oil output, the curves of production are very suggestive. The history of oil fields in the United States may be divided into three periods:

I. Period of unconscious application of certain geological factors (1859-1888).
II. Period of application of anticlinal principle (1888-1900).
III. Period of intensive application of geology (1900 to date).

In the first period, in spite of the unconscious application of geological strike through "degree lines," there was, as elsewhere explained, no real understanding of either stratigraphy or structure, and production increased very slowly. By 1888 it had already dropped off several million barrels per annum.

Several years before this date Doctor White began the application of the anticlinal principle to the location of pools in Pennsylvania and West Virginia, but the influence was most apparent from 1888 to 1892, when the production jumped from sixteen to thirty-six million barrels a year. From this maximum it has slowly declined.

The period of intensive application of geology began about 1900, with the greater utilization of the reports of the National Geological Survey, and was soon followed by the employment of geological experts and large corps of corporation geologists. In the Western fields the effect was very marked, as shown by figure 1; but the results were less apparent in the East, for the reason that the field was in its decline and the operators were very conservative. Geology, nevertheless, has probably had a material effect in sustaining production and giving it a much slower decline than it would otherwise have had.

STRATIGRAPHY

FORMATIONS REPRESENTED

Although most of the geological column from Cambrian to Carboniferous is represented in the strongly folded regions of the Appalachian Mountains and underlies the oil field proper, at least in its northern portion, much of it is beyond the present limits of the drill.

In northwestern Pennsylvania there is little Carboniferous except on the hilltops, but at the southwest corner of the State there is nearly 3,500 feet exposed at the surface or encountered in wells. The Devonian shales form much of the surface in northwestern Pennsylvania and are found in the wells in the southwest counties, in which they have been penetrated to a depth of not less than 4,000 feet. The 7,100-foot McDonald well, in this section, ended in the Salina formation, which would give to the Devonian a total thickness of more than 5,000 feet.

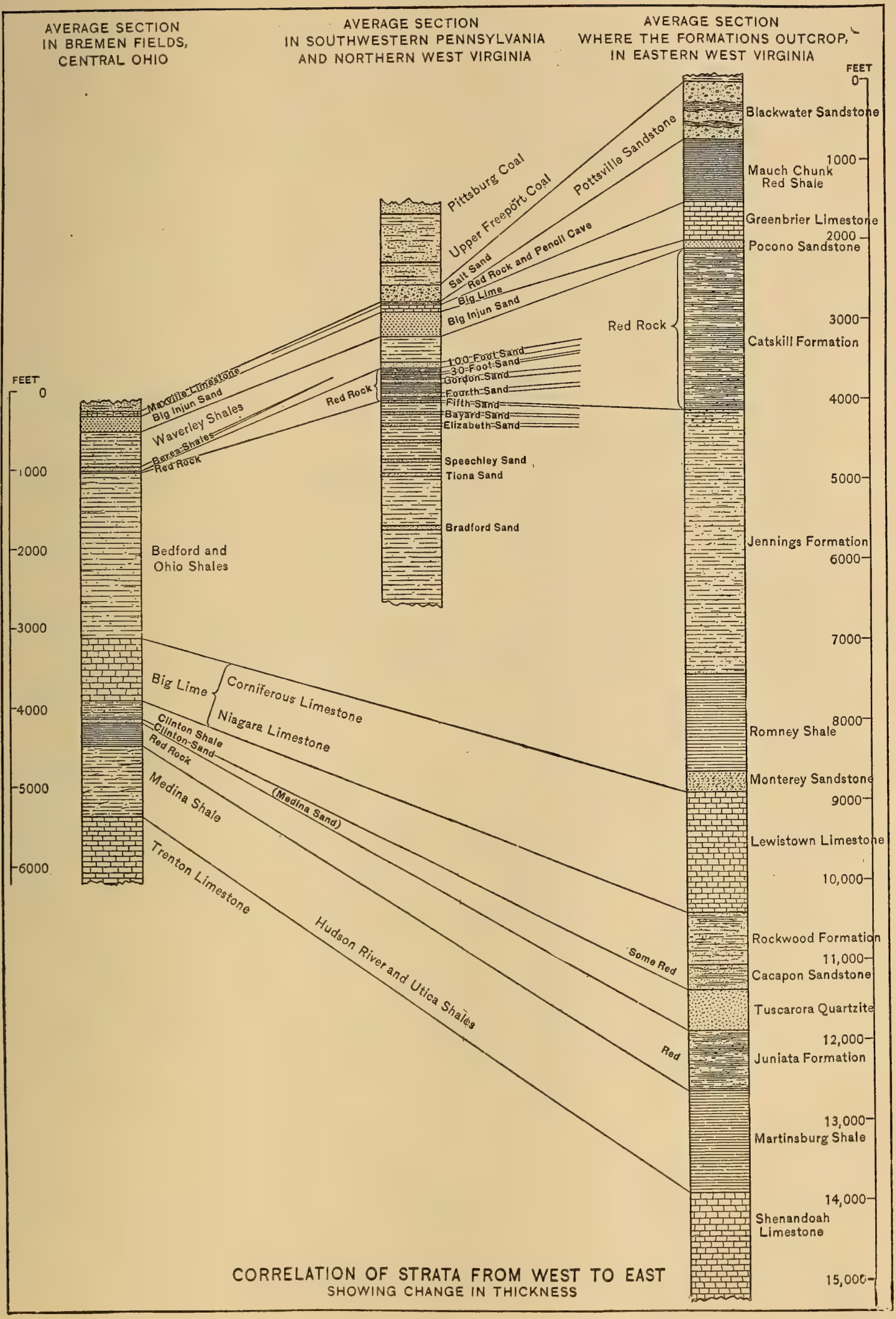
AVERAGE SECTION
IN BREMEN FIELDS,
CENTRAL OHIO
AVERAGE SECTION
IN SOUTHWESTERN PENNSYLVANIA
AND NORTHERN WEST VIRGINIA
AVERAGE SECTION
WHERE THE FORMATIONS OUTCROP,
IN EASTERN WEST VIRGINIA
FEET
0
1000
2000
3000
4000
5000
6000
Maxville Limestone
Big Injun Sand
Waverley Shales
Berea Shales
Red Rock
Bedford and
Ohio Shales
Big Lime
Corniferous Limestone
Niagara Limestone
Clinton Shale
Clinton Sand
Red Rock
Medina Shale
Trenton Limestone
(Medina Sand)
Hudson River and Utica Shales
Pittsburg Coal
Upper Freeport Coal
Salt Sand
Red Rock and Pencil Cave
Big Lime
Big Injun Sand
Pottsville Sandstone
Red Rock
100 Foot Sand
30 Foot Sand
Gordon Sand
Fourth Sand
Fifth Sand
Bayard Sand
Elizabeth Sand
Speechley Sand
Tiona Sand
Bradford Sand
Red Rock
Some Red
Red
FEET
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10,000
11,000
12,000
13,000
14,000
15,000
Blackwater Sandstone
Mauch Chunk
Red Shale
Greenbrier Limestone
Pocono Sandstone
Catskill Formation
Jennings Formation
Romney Shale
Monterey Sandstone
Lewistown Limestone
Rockwood Formation
Cacapon Sandstone
Tuscarora Quartzite
Juniata Formation
Martinsburg Shale
Shenandoah
Limestone
CORRELATION OF STRATA FROM WEST TO EAST
SHOWING CHANGE IN THICKNESS

FIGURE 3.—*Comparative stratigraphic Columns of Ohio, West Virginia, and Pennsylvania* (After F. G. Clapp)

In northern West Virginia substantially the same series and intervals are found as in Pennsylvania, but in southern West Virginia the thicknesses have changed considerably. The Pottsville sandstones and Greenbrier limestone have each thickened to several hundred feet, while the Pocono has largely disappeared and the Devonian shales have probably decreased in thickness from 4,000 to about 2,000 feet. In Kentucky the equivalent of the Pottsville has further increased in thickness, being about 1,000 feet thick, as compared to 150 feet in northern Pennsylvania, while the Devonian has thinned down to an insignificant 150 feet. In Tennessee there is a still further thickening of the higher Carboniferous beds, while the Pocono disappears and the Devonian thins to 50 feet. In the Warrior coal field of Alabama, lying west of the outermost strong fold, the Pottsville is 2,500 feet thick, while the Pocono is always, and the Devonian commonly, missing.

The foregoing statements of thicknesses apply to the beds of the basin lying to the west of the strongly folded area of the Appalachians in which the productive oil pools occur. The thicknesses in the mountains are quite different, the formations usually being much more strongly developed in the latter area.

The Devonian shales thin rapidly to the west as well as to the south. In southeastern Ohio their thickness has decreased to 3,000 feet, while in the central Ohio oil pools the Devonian representative, the Bedford shale, is only about 2,000 feet thick.

The accompanying table shows the comparative stratigraphic columns of the Carboniferous and Devonian series in various States, as compiled from publications of the United States Geological Survey and other sources.[11] The Silurian probably occurs at a depth of 8,000 to 8,500 feet in southwestern Pennsylvania and northern West Virginia, with the Trenton limestone of the Ordovician about 1,500 feet deeper. Neither are within the present limits of drilling. In Kentucky and Tennessee both are within reach of the drill in the western portion of the basin and along the flanks of the Cincinnati anticline, where they reach a thickness of several thousand feet. In Alabama the Silurian has largely disappeared, but the Ordovician still has a thickness of 1,000 feet.

OIL HORIZONS

General discussion.—In the Appalachian province the range of oil and gas horizons is almost coextensive with the geological column. Oil occurs

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[11] See Folios of U. S. Geol. Survey as follows: Rogersville (Pa.), No. 146; Buckhannon (W. Va.), No. 34; London (Ky.), No. 47; Briceville (Tenn.), No. 33, and Birmingham (Ala.), No. 175.

			Pennsylvania and northern West Virginia (Rogersville folio).	Southern West Virginia (Buckhannon folio).	Kentucky (London folio).	Tennessee (Briceville folio).	Alabama, Warrior coal field (Birmingham folio)
Carboniferous.	Permian.	Upper, barren.	Dunkard, 1100.				
	Pennsylvanian.	Upper, productive.	Monongahela, 400.	Braxton, 700.		Coal measures (not correlated), 2500.	
		Lower, barren.	Conemaugh, 700.	Upshur, 400.			
		Lower, productive.	Allegheny, 300.	Pugh, 400.	Lower coal measures, 500.		
			Pottsville, 150.	Pickens, 400.	Lee, 1000.	Lee, 1000.	Pottsville, 2500.
	Mississippian.		Mauch Chunk, 100.	Canaan shale, 600.	Pennington, 100.	Pennington, 300.	Pennington, 200.
			Greenbrier, 100.	Greenbrier 1st, 350.	Newman, 200.	Newman, 700.	Greenbrier, 200.
			Pocono, 600.	Pocono, 50.	Waverly, 350.		
Devonian.			Catskill, 500.	Hampshire, 800.	Chattanooga shale, 150.	Chattanooga shale, 50.	Chattanooga shale, 0—25. (Frog Mt sandstone ?) ?
			Chemung and Hamilton, 3500.	Jennings, 800+.			
			7450.	4500.	2300.	2050.	2925.

in the Trenton and Chazy in New York, while some of the highest natural pressures ever reported, about 1,500 pounds to the square inch,[12] were afforded by gas from the lowest beds of the Potsdam, next to the granite, in New York. In the Carboniferous, oil has been found up to horizons 300 feet or more above the Pittsburgh coal lying at the base of the Monongahela group of the Pennsylvanian series.

The upper Devonian formations yield the largest proportion of the petroleum afforded by the Appalachian field. There seems to have been abundant material in the shape of vascular plants with resistant tissues, spores, seed envelopes, etcetera, as well as fucoids, algæ, and micro- and macro-animal organisms of both marine and fresh-water forms. The abundance of material, in connection with the presence of salt water and the occurrence of good reservoirs and thick shale cap-rocks, made the conditions especially favorable to the formation and storage of petroleum. The depth of the strata from the surface has also been a contributing factor of importance in the retention of the oil in a large part of the oil field because of the barrier imposed to upward escape or the entrance of fresh water from above.

In the Carboniferous series there are more frequent limestones, and the sandstones are thicker, tending to permit dissemination of the oil. The cap-rocks are thinner, and the nearness of the formations to the surface lessens the resistance to escape and sometimes permits the entrance of fresh waters. Nevertheless, there are several good oil sands in the Carboniferous in the northern part of the Appalachian field.

The Trenton lifestone, because of its great depth, is unavailable to wells except where it rises on the flanks of the Cincinnati anticline in central Kentucky, Tennessee, and northern Alabama, west of the main oil belt lying along the west flank of the Appalachians.

New York.—The greater part of the oil of the State comes from the Bradford and other sands not far above or below it in the Chemung, but traces of oil or gas are found in most of the limestones and sandstones and in several of the shales down to the Potsdam, especially in the Niagara and Trenton limestones, the Oriskany, Medina, and Potsdam sandstones, the Utica shale, etcetera. The formations below the Chemung, however, lie mostly outside the limits of the Appalachian field proper.

Pennsylvania and northern West Virginia.—The producing horizons in Pennsylvania and northern West Virginia range from the Carrol sand of the Monongahela formation, 300 feet above the Pittsburgh coal, to the Kane sand of the Chemung, 3,770 feet below the same datum. The Clinton sand, not yet penetrated, is expected at 8,000 to 8,500 feet, while the Trenton limestone lies at 9,500 to 10,000 feet from the surface.

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[12] F. H. Oliphant: "Catalogue of Metric Metal Works for 1909," p. 38.

A list of the oil sands of the Pennsylvania-West Virginia district, as compiled from various publications, is given in the following table:

Oil Horizons of Pennsylvania-West Virginia District

	Distance above (+) or below (—) the Pittsburgh coal in feet
Carboniferous.	
Pennsylvanian.	
Monongahela formation (Upper Productive measures).	
Carrol sand (Uniontown sandstone), productive in West Virginia only	+ 300
(Pittsburgh Coal horizon)	
Conemaugh formation (Lower Barren measures).	
Murphy, Shallow, Little Dunkard, or First Cow Run sand (Saltsburg sandstone)	— 200
Big Dunkard or Cow Run sand (Mahoning sandstone)	— 500
Allegheny formation (Lower Productive measures).	
Second Cow Run sand (Freeport sandstone)	— 600
Gas sand	— 800
Pottsville formation (Salt sand).	
Johnson Run sand (Homewood sandstone)	— 900
Upper Salt sand (Lower Conoquenessing sandstone)	— 950
Middle Salt sand (Lower Conoquenessing sandstone)	—1050
Lower salt (Sharon conglomerate)	—1150
Mississippian.	
Mauch Chunk formation.	
Maxton or Cairo sand (of West Virginia)	—1200
Greenbrier limestone ("Big Lime")	—1250
Pocono formation (Big Injun sand).	
Keener sand	—1300
First, Second, and Third Pay sands (Top)	—1400
Squaw sand	—1450
Wier sand	—1500
Devonian.	
Catskill formation.	
Upper Gas sand (sometimes placed in Pocono)	—1550
Berea or Thirty-foot sand (sometimes placed in Pocono)	—1750
Murraysville or Butler sand	—1800
Gantz, First, or Hundred-foot sand	—1850
Fifty-foot sand	—1900
Ninevah, Thirty-foot, or Second sand	—2000
Gray, Gordon Stray, or Boulder sand	—2100
Gordon, Third, or Campbells Run (?) sand	—2150
Fourth sand (Gordon of West Virginia?)	—2200
Fifth sand (McDonald of West Virginia?)	—2250
Bayard sand	—2400

Chemung formation.	
Elizabeth or Sixth sand	—2600
Warren First sand	—2700
Warren Second sand	—2800
Tiona sand	—2900
Speechley sand	—3000
Balltown or Cherry Grove sand	—3120
Sheffield or Cooper sand	—3320
Bradford sand	—3430
Second Bradford sand	—3480
Elk sand	—3650
Kane sand	—3770

Of the 37 producing sands enumerated in the table, 15 are in the Carboniferous and 22 in the Devonian. They are distributed as follows:

Pennsylvanian:		
Monongahela (Upper Productive)	"White sands"	1
Conemaugh (Lower Barren)		2
Allegheny (Lower Productive)		2
Pottsville		4
Mississippian:		
Mauch Chunk (including Greenbrier limestone)		2
Pocono		4
Devonian:		
Catskill	"Black sands"	11
Chemung		11
		37

The lowest sand at present productive in West Virginia is the Bayard, 2,400 feet below the Pittsburgh coal, near the base of the Catskill. The Elizabeth sand yields gas near the Monongahela River in southwest Pennsylvania, and the Tiona, Speechley, and Bradford sands in the district east of Pittsburgh, but the pools drawing from these formations are mostly in the northwestern portion of the State.

Ohio.—The highest producing formation in southeastern Ohio appears to be the First Cow Run sand of the Conemaugh formation. The Salt, Big Injun, and Berea sands are well developed. The lowest important sand in southeast Ohio is the Gordon of the Catskill. The lower sands, including the Elizabeth and Bradford, have mostly pinched out. Most of the producing sands are the same as in adjoining portions of Pennsylvania and West Virginia. The largest gas field in the world and some oil pools are found in the so-called Clinton (Medina) of central Ohio. The Trenton does not produce within the limits of the Appalachian field proper.

Kentucky.—The principal producing sands of Kentucky are the Salt sands of the Pottsville, the Squaw sand of the Pocono, the Berea and Gantz of the Catskill horizon, and the Trenton Corniferous or limestones.

Tennessee.—Oil is found in this State mainly in the Newman (Greenbrier) limestone of the Mauch Chunk horizon and in the Trenton.

Alabama.—There is no separately recorded production in Alabama, but oil shows occur in the Pennsylvanian sandstones, the Mississippian sandstones and limestones, and in the Trenton limestone.

STRUCTURE OF THE APPALACHIAN OIL FIELD

GENERAL RELATIONS

The Appalachian oil field lies in the east half of a broad synclinorium which is bounded on the north by the pre-Devonian formations of southern New York and Ontario, on the east by the Appalachian Mountains, and on the west by the Ohio and Tennessee domes of the Cincinnati anticline.

The synclinorium is broadest at its northern limit, where the portion of the basin occupied by Carboniferous rocks approaches a width of 300 miles. From here it tapers gradually southward until in northern Alabama it is less than 30 miles from the outermost strong fold of the Appalachians to the Ordovician area of the Tennessee dome.

STRUCTURE IN PENNSYLVANIA

In northeastern Pennsylvania the strong folds of the anthracite coal fields die off northward and northwestward through a series of progressively weaker folds into the gently undulating or almost flat structures of the Elmira region of south-central New York. Substantially the same sequence is found in central Pennsylvania, the folds becoming progressively weaker northwestward from the Allegheny Front to the flat district north of Bradford, Pennsylvania, and in Cattaraugus County, New York.

In southwestern Pennsylvania two strong and sharp outlying folds, giving rise to what are known as Chestnut and Laurel ridges, are found west of the Allegheny Front, the outermost being over 30 miles away. West of these structures the dips flatten materially, the folds being comparatively low and irregular. The change from the mountainous to basin structure is not associated with noticeable faulting in Pennsylvania. Most of the pools occur on anticlines, with a few on structural terraces, or, in the absence of water, in synclines.

STRUCTURE IN WEST VIRGINIA

The structure in northern West Virginia is practically the same as in southwestern Pennsylvania. The Chestnut and Laurel ridge anticlines become rapidly weaker to the south, however, although other outlying ridges of considerable strength take their place. The transition from the sharply folded belt into the more moderately folded and undulating districts occurs without material faulting. Practically all the pools are associated with anticlines (or synclines when water is absent), although productive structural terraces exist.

In southern West Virginia the beginnings of a distinctly different type of structure, which becomes progressively more marked in Kentucky, Tennessee, and Alabama, are seen. The sharp outlying folds west of the Allegheny front are still present, but instead of grading outward through well defined folds, as in the northern part of the State and in Pennsylvania, the beds dip outward (westward) in a comparatively structureless homocline to the center of the basin. The anticlinal warpings are low and somewhat poorly defined.

STRUCTURE IN KENTUCKY

In Kentucky the change in structure noted in southern West Virginia becomes more marked. The outlying folds of moderate strength are replaced by the stronger folds of the Appalachian Mountain type, the mountainous belt reaching farther westward and terminating in a faulted front. The beds, which in southern West Virginia dip westward from the disturbed area in a homocline many miles in width, here become first flat, then dip in a reversed direction, or eastward, toward the sharp fold or fault marking the western face of the mountains. The deepest part of the basin is, therefore, at its extreme eastern edge. The warping of the homocline is very moderate and most of the pools appear to be found on terraces.

STRUCTURE IN TENNESSEE

The eastward-dipping homocline of south Kentucky also extends across Tennessee. In this State the western edge of the strongly folded area is everywhere marked by overthrust faults, with the basin beds upturned beneath them. The basin is deepest along the east edge, except in south Tennessee, where there is an outlying anticline similar to that of Chestnut Ridge in Pennsylvania, but with much stronger dips and with a fault of considerable magnitude on its west face. This lies about 15 miles west of the normal front of the folded area, which approximately follows the

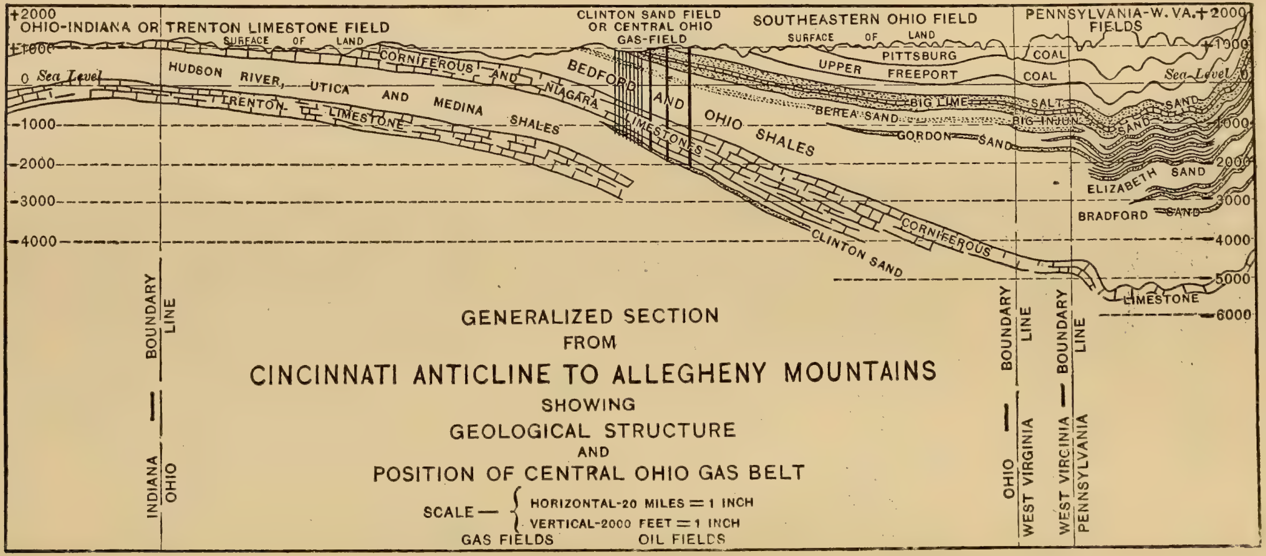
+2000
OHIO-INDIANA OR TRENTON LIMESTONE FIELD
SURFACE OF LAND
+1000
0 Sea Level
-1000
-2000
-3000
-4000
HUDSON RIVER, UTICA AND MEDINA SHALES
TRENTON LIMESTONE
CORNIFEROUS AND NIAGARA
CLINTON SAND FIELD OR CENTRAL OHIO GAS-FIELD
BEDFORD AND OHIO SHALES
LIMESTONES
SOUTHEASTERN OHIO FIELD
SURFACE OF LAND
PITTSBURG
UPPER FREEPORT
BIG LIME
BEREA SAND
GORDON SAND
CLINTON SAND
CORNIFEROUS
PENNSYLVANIA-W. VA. FIELDS
+2000
COAL
COAL
+1000
Sea Level 0
SALT SAND
BIG INJUN SAND
SAND
1000
2000
ELIZABETH SAND
3000
BRADFORD SAND
4000
5000
LIMESTONE
6000
INDIANA — BOUNDARY
OHIO LINE
OHIO — BOUNDARY
WEST VIRGINIA LINE
WEST VIRGINIA — BOUNDARY
PENNSYLVANIA LINE
GENERALIZED SECTION
FROM
CINCINNATI ANTICLINE TO ALLEGHENY MOUNTAINS
SHOWING
GEOLOGICAL STRUCTURE
AND
POSITION OF CENTRAL OHIO GAS BELT
SCALE — HORIZONTAL-20 MILES = 1 INCH
VERTICAL-2000 FEET = 1 INCH
GAS FIELDS
OIL FIELDS

FIGURE 4.—*Geological Section from Cincinnati Anticline to the Allegheny Front*

(After F. G. Clapp)

course of the Tennessee River. There are strong cross-faults locally in north Tennessee. The eastward-dipping homocline is warped and has occasional weak anticlines.

STRUCTURE IN ALABAMA

The structural features of south Tennessee continue into Alabama. The front of the main folded belt extends southwestward from the northeast corner of the State through Birmingham to a point east of Tuscaloosa. The outlying fold continues southwestward more than 100 miles before subsiding to a subordinate feature. In the north the basin is of greatest depth in the vicinity of the thrust-fault on the west face of this anticline; but as the fault dies out, the center of the trough trends gradually westward until it lies some 15 miles west of the anticline in the Birmingham district (Warrior Coal Field). On the farther side of the trough the beds rise northwestward in a homocline rising toward the uplift of central Tennessee. Most of the oil appears to occur on structural terraces.

Origin of Oil in the Appalachian Field

In a general paper like the present it does not seem desirable to go into the question of origin of oil in any detail.

It may be said at the start, however, that there appears to be no evidence whatever in the Appalachian field to support any of the inorganic sources or processes which have been postulated through the reaction of carbon-dioxide on alkaline metals, of water on iron carbides, or of solfataric gases on limestone.

On the other hand, there is an abundance of organic material of both animal and vegetable types in the rocks, the most important of which are as follows:

Animal........	Fish. Mollusks. Micro-organisms, etcetera.
Vegetable......	Woody or cellulose plants, spores, seed envelopes, etcetera. Fucoids. Algæ. Micro-organisms, etcetera.

All of the animal and vegetable forms listed above are present in the rocks of the Appalachian field. All have been definitely proven to be capable of affording oily hydrocarbons by natural distillation. It seems likely that all have played a part in the production of the Appalachian oils. It is probable, however, that the greater part of the latter are derivatives of decay-resisting elements such as spore and pollen exines, seed envelopes, and certain cuticles provided with resinous, waxy, or oily protective substances mixed with other fat-, oil-, or albuminoid-producing animal and plant ingredients high in hydrogen and low in oxygen found in organic muds.[13]

The following outline shows the principal stages in the origin and distribution of Appalachian oils, as the processes are understood by the writer:

Stages in Origin and Distribution of Appalachian Oils

(Stages often overlapping)

1. Deposition of organic muds and slimes, alternating with sands and sometimes calcareous beds.
2. Saturation (usually) with salt or salty waters (coming from overlying or underlying beds where original accumulations were of fresh-water origin).
3. Burial (usually) by thick overlying sediments.
4. Bio-chemical (bacterial) alteration and formation of oily substances.
5. Occurrence of oil in minute particles widely disseminated.
6. Migration of oil, largely upward, by capillarity, etcetera.
7. Collection of oil in porous sands or other reservoirs.
8. Gravitational separation of oil from water.
9. Segregation of oil in small pools in slightly undulating and still unconsolidated deposits at moderate depths, assisted in cases by hydrostatic movements, gas pressure, etcetera.
10. Application (usually) of increasing load following continued deposition.
11. Application of dynamic forces, with warping or folding.
12. Cementation, with reduction of pore spaces.
13. Migration of original oils, with collection in anticlines or below other obstructions where water is present, or in synclines where water is absent.
14. Formation of new oils by dynamo-chemical agencies.
15. Dynamo-chemical alteration of certain of the original oils.
16. Separation and rediffusion of some of the original oils, with the leaving behind of solid residues.
17. Evolution of much new gas.
18. General movement of oils and gas upward.
19. Changes in composition of oils by filtration in upward passage.
20. Changes in composition of oils by intermixture with one another.
21. Changes in composition of oils by absorption of gas.
22. General arrangement of oils according to stage of metamorphism as indicated by carbon ratio of coals (see page 649), with light oils nearest zone of greatest dynamo-chemical activity and in deepest beds.

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[13] David White: "Some Relations in Origin between Coal and Petroleum." Jour. Wash. Acad. Sci., vol. 5, March 19, 1915, p. 192.

RELATIONS OF APPALACHIAN OILS TO STRUCTURE

PRINCIPAL FACTORS

The distribution of oil in the pools in which it is now found is dependent upon its origin, migration, and method of segregation on the one hand, and upon the composition, texture, stratigraphic form, dynamic structure, and confining agents of the reservoirs on the other. The former have been briefly referred to under "Origin of appalachian oils."

In the past, most geologists, while recognizing the existence of other factors of importance, have given by far the greatest weight to dynamic structure. A reaction has been under way for some time, however, and there has been a growing tendency on the part of some to minimize the value of structure. It has been pointed out[14] that in Pennsylvania and West Virginia about 75 per cent of the oil pools fail to cross the axes of the folds on which they lie. This, however, is hardly an argument against the importance of structure, since it is not to be expected that *oil* pools will cross the axes except at the terminations of folds or local bulges, their normal position being on the sides. The partial condemnation of structural terraces[15] is apparently based mainly on theoretical considerations and does not seem to be warranted by the observed field relations.

It is probably true that many have given too little consideration to composition, cementation, stratigraphic form, and other factors pertaining to reservoirs; but, as in all reactions, there is danger of the pendulum swinging too far. It must not be forgotten that, aside from stratigraphy, structure is the only factor that may be predetermined in advance of drilling in new territory, and that operations based on anticlines and structural terraces have been essentially successful in almost every field. Unquestionably, however, more attention should be paid to other factors than has been customary in the past, especially on the part of corporation geologists having access to records and other development data. Many sands have individualities and trends that may be made use of to advantage in new fields.

STRUCTURES

The principal structures affecting the collection of oil in pools are given below. Practically all of them are represented in the Appalachian field.

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[14] W. E. Bernard: Thesis, University of Pittsburgh, "Relations of folds to the oil pools of Pennsylvania and West Virginia," pp. 27-28. Quoted by Johnson & Huntley, "Principles of Oil and Gas Production," John Wiley & Sons, 1916, p. 71.

[15] Johnson & Huntley: Ibid., p. 72.

TABLE III.—*Principal Oil Structures* (*Dynamic*)

Class of structure.	Structural units.	Subordinate structures.
Anticlinal (in wet sands).	Geanticline. Anticline. { Isolated. Associated with synclines. Intersecting anticlines. Domes. { Normal. Salt domes.	Bulges on crest. Plunging ends. Spurs Structural terraces. Saddles (between synclinal depressions on same axis.
Synclinal (in dry sands).	Geosyncline. Syncline. { Isolated. Associated with anticlines. Intersecting synclines. Bowl-shaped depressions.	Depressions in bottom. Axial plunge lines. Lateral sags Structural terraces.
Homoclinal.	Anti-homocline (convex surface). Syn-homocline (concave surface). Plane-homocline (plane surface).	Structural terraces. { Dip reduced. Dip flat.
Aclinal (flat).	Absent in Appalachian field.	Original structures only.

A word may be said regarding the terms "homoclinal" and "aclinal." Homocline is a term introduced by R. A. Daly[16] for a dip in one direction, but not necessarily of like degree at all points, as in a monocline. Anti-homocline has been used to designate a homocline of convex surface and syn-homocline one of concave surface.[17] Monocline is restricted by Daly and others to drops or one-limbed flexures in flat or slightly inclined rocks. Acline has been used to designate flat-lying beds—that is, without dip.

RESERVOIRS

Of equal importance to structure is the character of the reservoirs. Many different classifications have been proposed. That followed by the writer is given in the accompanying table, page 642.

It hardly needs to be said that the metamorphic and igneous classes of reservoirs are of scientific rather than practical interest, so far as the Appalachian oil field is concerned. Oil has been reported in igneous rocks at the contact with sedimentaries in Quebec, in basalts in Mexico and Oregon, and in granite in Wyoming, and may likewise be expected under

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[16] Canadian Dept. of Mines, Geol. Survey, Memoir 68, p. 53.
[17] Johnson & Huntley: Ibid., p. 64.

TABLE IV.—*Classification of Oil Reservoirs*

Rocks.		Original openings.	Chemically formed openings.	Dynamically formed openings.	Forms of reservoirs.
Sedimentary (oil indigenous).	Sands and conglomerates	Super-capillary pores.	Openings from resolution of cement Enlarged bedding planes. Enlarged fractured planes.	Joints, fissures, faults, separated bedding planes, crushed zones, etc.	Bedded. Even-bedded porous rocks. Regular lenses. Depositional. Dependent on cementation. Dependent on solution. Dependent on lateral variation of texture. Irregular lenses. Depositional. Originally warped. Bars, spits, etc. Current deposits. Erosional (unconformities). Dependent on cementation. Dependent on solution. Planes. Normally vertical. Faults, fissures, joints, and crushed zones. Normally horizontal. Bedding planes.
	Coals.	Parting planes.	Rare.		
	Shales.	Capillary interstices.	Rare.		
	Limestones.	Capillary interstices.	Dolomotized limestone. Enlarged bedding planes. Enlarged fracture planes. Solution passages.		
Metamorphic (oil not indigenous).		Inherited openings only.	Solution passages and fracture enlargements in limestones.	Joints, fissures, faults, crushed zones, cleavage planes, interlamillar openings due to contortion.	Same as sedimentary.
Igneous (oil not indigenous).		Vesicles.	Probably absent.		Extrusive. Lava flows, etc. Intrusive. Dikes, sills, batholites, etc.

certain conditions in joints, etcetera, of metamorphic rocks where overlain by oil-bearing sediments.

The greater number of the reservoir forms listed are too well known to require further explanation. Among the irregular lenses of depositional origin is mentioned "originally warped" beds. These are beds which, like the lower gas-bearing layers of the Potsdam, were deposited as somewhat uniform mantles over underlying unconformable surfaces and possess original curvatures similar to those elsewhere formed by folding. Fossil bars, spits, and allied deposits are more frequent than is usually imagined. Current deposits filling channels in older or in contemporaneous beds are by no means uncommon. They are almost invariably coarser than the surrounding material, even conglomeratic.

CONFINING AGENCIES

These are likewise of great importance, since favorable structures and adequate reservoirs will be unavailing in the absence of agents capable of effecting the retention of the oil. The

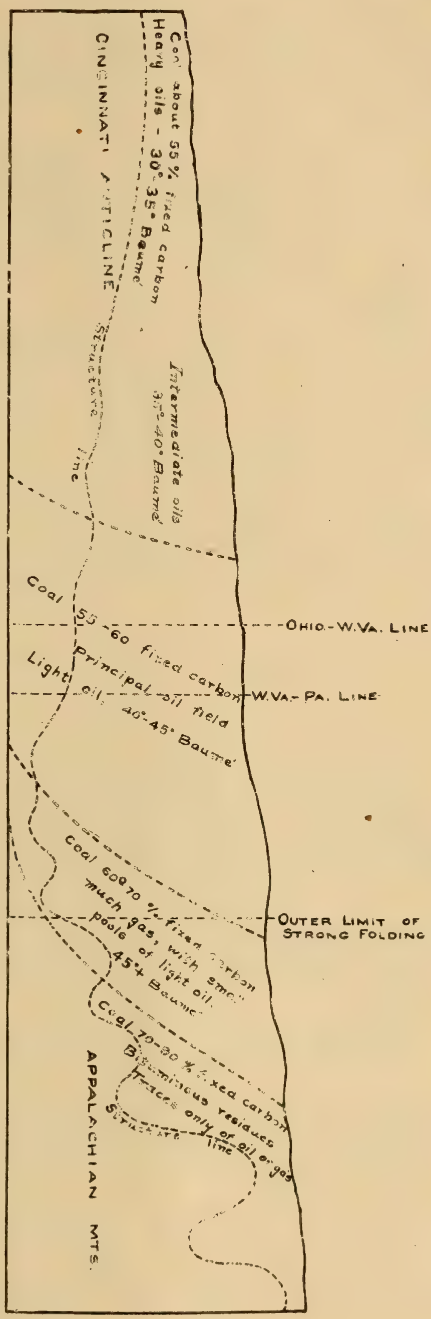
Coal about 55% fixed carbon
Heavy oils - 30°-35° Baumé
CINCINNATI ANTICLINE
Structure line
Intermediate oils 35°-40° Baumé
Coal 55-60 fixed carbon
Light oil
Principal oil field
40°-45° Baumé
OHIO-W.VA. LINE
W.VA.-PA. LINE
Coal 60 to 70 fixed carbon
Much gas, with small pools of light oil
45° Baumé
OUTER LIMIT OF STRONG FOLDING
Coal 70-80 % fixed carbon
Bituminous residues
Traces only of oil or gas
Structure line
APPALACHIAN MTS.

FIGURE 5.—*Generalized Section showing Relation of the Distribution of Appalachian Oils of various Gravities to the Zone of dynamic Disturbance and to the fixed-carbon Percentages in Coals*

principal retaining agents are listed in the following table, in which are given confining agencies in oil pools other than structural limitations:

TABLE V.—*Confining Agents in Oil Pools (other than structural Limitations)*

Confining agents.	Covers (vertical factors of limitation—external).	Clays and shales. Marls and limestones. Igneous sills.	Regular contacts. Solutional irregularities of contacts. Unconformable contacts.	
	Lateral factors of limitation.	Internal factors.	Thinning out of beds. Lateral change in grain. Lateral change in composition. Lateral change in cementation. Limits of action of solution. Asphaltic or paraffin closure.	
		External factors.	Unconformities.	Erosional. Overlap.
			Faults.	Opposition of impervious beds. Crushed or shear zones.
			Veins.	Depositional matter. Selvage.
			Igneous dikes, plugs, irregular sills, etc.	

Of the covers, shales are the most common and important in the Appalachian field. Igneous sills have never been encountered in this province, but dikes are known in the midst of the oil field and sills may occur. Of the internal confining agencies, lateral changes of grain are the most important. Almost nowhere is a single bed productive, without at least local interruptions, for more than a few miles. Usually it is a change toward tightness or fineness of grain that marks the limits of productivity.

Cementation is a close second to grain in determining the extent of productivity at a given point. Variations in cementation, either original or due to solution, undoubtedly affect the location and extent of the oil accumulations in many of the Appalachian sands.

The pinching out of lenses is another limiting factor of great importance. Unconformities at the tops of producing sands undoubtedly exert a considerable influence on the distribution of oil, at least locally. Closure of sands by asphaltic or paraffin residues are not common in the Appalachian field, but may occur in some instances.

The other external lateral factors of limitation, including faults, veins, and dikes, with their associated selvages, shear zones, etcetera, are probably of little importance in the Appalachian field, although both faults and dikes are known.

DIPS

In general, oil is found in the Appalachian field only where the dips are under 3 degrees, although an occasional pool is found where the prevailing dips are from 3 to 10 degrees, as at Gaines, Pennsylvania. Johnson & Huntley[18] found that in a district examined by them in southeastern Ohio and northern West Virginia the largest number of pools occurred where the average dip was 20 feet or less per mile. About three-fourths as many were found where the dips were 40 feet, and a third as many where they were 60 feet per mile. About 85 per cent of the pools were in rocks dipping 1 degree or less.

Somewhat similar relations obtain throughout the entire Appalachian oil field, although the percentage of pools in the beds of the very lowest dip are probably somewhat lower, taking the district as a whole, than in the district mentioned.

PRODUCTION

DEVELOPED AREA

The coal basin, or synclinorium, between the Appalachian Mountains and the Cincinnati anticline is about 800 miles long, and ranges downward in width from 300 miles at the New York line to 150 miles in Kentucky, 50 miles in Tennessee, and 25 miles in Alabama. The total area is about 70,000 square miles.

While the greater part of this area is oil- or gas-bearing to some extent, most of the production comes from a strip about 25 miles broad, lying parallel to and just outside the westernmost strong fold of the Appalachians from the New York line to central West Virginia, a distance of 300 miles. The area is 7,500 square miles, or a little over 10 per cent of the area of the basin.

The area of the Appalachian oil field has been estimated at 2,504 square miles, which would be equivalent to about 3.6 per cent of the basin and 33 per cent of the oil belt.

The developed area by States is as follows:[19]

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[18] Ibid., p. 80.

[19] David T. Day: "Map of Known Producing Oil and Gas Fields of the United States in 1908." Min. Res. U. S., 1908, pt. 2, pl. 1.

Area of Appalachian Oil and Gas Pools

	Oil	Gas
New York	300	540
Pennsylvania	2,000	2,730
West Virginia	570	1,000
Southeastern Ohio	115	110
Kentucky	400	290
Tennessee	69	....
Alabama	50	40
	2,504[20]	4,710

WELLS

In the following are given certain well statistics which throw light on the present activity of operations:

Well Statistics in Appalachian Field for 1914

Wells drilled	6,849
Wells obtaining oil	4,272 (63 per cent of total drilled)
Wells obtaining gas	1,320 (19 per cent of total drilled)
Dry holes	1,257 (18 per cent of total drilled)
Wells abandoned	2,200 (2 per cent of existing wells)
Total existing wells	105,000
Average yield per day for new wells	10½ barrels
Average yield per day for all wells	6/10 barrel

The number of wells drilled in 1914 (6,849) appears on the face to compare favorably with the 8,000 to 9,000 drilled in the years of great activity about 1900; but, as a matter of fact, many of the new wells credited to 1914 were old wells redrilled. To the same fact is possibly due in part the fairly small number of dry holes, the proportion of which amounted to 25 per cent in the period of active development from 1891 to 1900. In fact, in the Pennsylvania district, where the drilling was limited largely to the deepening of old wells or to marginal extensions of the existing pools, the proportion of dry holes was only 12 per cent.

PRODUCTION STATISTICS

Commercial production began with the opening of the Drake well in 1859, the yield for that year being about 2,000 barrels. The following year the output jumped to 500,000 barrels, and the third year to 2,113,609 barrels, after which it rose slowly, with an occasional setback, to 30,221,261 barrels in 1882, then, after a decline to 16,941,397 in 1888, to 35,848,777 in 1891 and 36,618,171 in 1900, after which it slowly declined to 24,101,048 in 1914.

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[20] Considerable potential oil territory is probably included with that actually producing, especially in Kentucky, Tennessee, and Alabama.

The following table gives an analysis of the production in 1914, while figure 2 shows by curves the relation of the Appalachian production to that of certain other American fields:

1914 Production in Appalachian Field

	Average daily yield		
	New wells (barrels)	All wells (barrels)	Total production (barrels)
New York	2	.2	938,974
Pennsylvania	3	.4	8,170,335
Southeastern Ohio	14	.7	4,809,265
West Virginia	23.5	1.8	9,680,033
Kentucky	13	1.3	502,441
Entire field	10.5	.6	24,101,048

Comparing the Appalachian with other important American fields, it is found that its production in 1914 was about 3,000,000 barrels more than that of Illinois, 4,000,000 more than Texas, 3,000,000 more than Mexico, and 10,000,000 more than Louisiana.

The production for 1914 was slightly more than that of Mexico, twice that of Roumania, twice that of the Dutch East Indies, three times that of Burma, and five times that of Galicia. The only foreign field surpassing the Appalachian in production is that of Russia, whose output in 1914 was a little over two and a half times that of the former district.

FUTURE OF THE APPALACHIAN OIL FIELD

IN GENERAL

The problem of the future development and length of life of the Appalachian oil field is one into which many factors enter, the influence of several of which cannot be determined at this time. Some of the more important evidences bearing on the future of the field are considered in the following paragraphs:

EVIDENCE OF STRATIGRAPHY

In Pennsylvania and northern West Virginia there are approximately 3,500 feet of Carboniferous beds and 4,000 feet of Devonian shales which contain sands likely to be productive of oil or gas. Of the 37 oil sands listed in the table on page 633, 15 are in the former and 22 in the latter. The production from the Devonian has far exceeded that from the Carboniferous.

Going southward, the Devonian increases somewhat in thickness in the mountainous regions of West Virginia, where some 6,000 feet of the shaly series are probably present, but it thins rapidly toward the west. In the Buckhannon quadrangle, some 25 miles from the eastern border of the basin, probably not much over 2,000 feet are represented.

In Kentucky, while reaching a thickness of 1,000 to 1,250 feet in the folded mountainous region, only 150 feet of the Devonian are present in the basin.

In Tennessee some 900 feet are found in the mountains, but only 50 feet in the basin, and even this is sometimes cut out by erosion. Ashley[21] states that of 35 oil horizons recognized in Pennsylvania, 26 have no representation in Tennessee, largely because of the thinning out of the Devonian, while 4 more occur only in the hills, which leaves only 5 stratigraphic horizons in common.

In Alabama the Devonian is reduced to a thickness of 25 feet where present, and is often cut out entirely by unconformity.

From the above it will be seen that 75 per cent or more of the northern petroliferous horizons are absent south of central West Virginia. There is, on the other hand, a considerable increase in the thickness of the Pottsville; but, unfortunately, so far as testing has shown, there has been nothing to encourage the expectation of commercial oil.

The stratigraphy, considered by itself, tends to indicate that comparatively little oil will be found from southern West Virginia southward across Kentucky, Tennessee, and Alabama. While small pools will undoubtedly be discovered from time to time, large developments, such as might materially raise the production or prolong the life of the Appalachian field, are not, in the light of our present knowledge, to be anticipated.

EVIDENCE OF STRUCTURE

West of the strong outlying folds paralleling the Allegheny front at a distance of 25 miles or more, the general structure is favorable to oil throughout the entire oil belt from southern New York to central Alabama.

In Pennsylvania, low folds, structural terraces, and warped homoclines are all present in good development over practically the whole area of the basin west of the line mentioned. The same is true of northern West Virginia. Toward the Kentucky line the folds become less conspicuous, although by no means absent, the predominant structural feature being the somewhat warped westward-dipping homocline. Within the State of Kentucky the dip of the homocline first flattens, then changes to a westward inclination, although still retaining structural warpings favorable to oil.

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[21] Geo. H. Ashley: Res. of Tenn., vol. ii, pp. 262-272.

In Tennessee the same warped eastward-dipping homocline prevails, with a marked outlying fold a few miles from the eastern border. Essentially similar structure exists in Alabama.

Notwithstanding the overthrust faults along the boundary between the Appalachian folds and the basin from the Kentucky line southward, the structure is distinctly favorable to the occurrence of oil at many points. In itself this would favor the future development of profitable pools in the region south of West Virginia; but, unfortunately, as noted elsewhere, other factors entering into the problem seem to make such development unlikely.

EVIDENCE OF CHARACTER OF RESERVOIRS

In Pennsylvania and most of West Virginia there are porous sands affording ideal reservoirs for oil, with cap-rocks for confining the same, at a large number of horizons in both the Carboniferous and Devonian strata. Going south, however, there is a distinct deterioration in the character of the reservoirs. In Tennessee it is found that the sands are very close and tight and the limestones commonly without the porosity, due to dolomitization, necessary to make them available as reservoirs.[22] Most of the oil found has been reported from crevices resulting from solution or weathering in the portions of the limestones near the surface.

EVIDENCE OF DEGREE OF DYNAMO-CHEMICAL ALTERATION

The principle recently advanced by David White,[23] that there is a definite and fixed relation between the distribution of oils and the fixed carbon of pure coals, opens a new field of thought. If the postulated relation can be established, as now seems likely in spite of the numerous variations and exceptions, it is likely to be the most important discovery pertaining to oil since the development of the anticlinal principle. It affords a measure of dynamo-chemical change or metamorphism, of the amount of which there has hitherto been no clue, and explains many puzzling features in the occurrence and distribution of oil and gas. It is of the greatest value in determining prospects in new territory.

Applying the principle to the Appalachian field, it is found that the occurrence of 65 per cent to 70 per cent of fixed carbon in pure coals establishes a sort of dead line as regards commercial deposits of oil or gas. Where coals range from 60 to 65 per cent, fixed carbon gas may be found in quantity, but little commercial oil. Where coals range from 55 to 60 per cent, fixed carbon oils are found in abundance, with abundant gas.

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[22] M. J. Munn: Tenn. Geol. Survey, Bull. 2-E, pp. 37-38.

[23] "Some Relations in Origin between Coal and Petroleum." Jour. Wash. Acad. Sci., vol. 5, no. 6, March 19, 1915, pp. 189-212.

The 60 per cent carbon line, supposed to mark the eastern limits of most of the commercial oil deposits, follows parallel to the Allegheny front, just outside the outermost strong fold (Chestnut Ridge, etcetera) from northern Pennsylvania to southern West Virginia. Here it turns abruptly west, crossing the State to a point south of Huntington; then bends south again, running not far from the eastern edge of the Ordovician limestones of the Cincinnati anticline across Kentucky and Tennessee into Alabama, figure 1, page 619, and figure 5, page 643.

Assuming the correctness of the postulated relationship of the oil to fixed carbon of the coals, we find that instead of the entire area of the basin between the Appalachians and the Cincinnati anticline being available, as in Pennsylvania, West Virginia, and Ohio, only a narrow strip is left between the 60 per cent carbon line and the outcropping limestones of the geanticline, in which testing has shown the cover to be thin and the reservoirs few in number and poor in character.

There is apparently little hope of the discovery of large pools of oil in Kentucky, Tennessee, or Alabama. This conclusion coincides with those based on the stratigraphy and the character of the reservoirs, and reinforces the general conclusion that in spite of favorable structure neither the future production nor the life of the Appalachian field are likely to be greatly affected by discoveries in this section.

The relation of the carbon of coals to oil also tends to indicate that comparatively little is to be expected from future developments in the extreme northeastern portion of the Appalachian field, as in the Gaines region, or the stronger anticlines or slopes near the Allegheny front. It does not, however, preclude the discovery of small pools.

FUTURE INFLUENCE OF GEOLOGY

It has been elsewhere noted that the production of the Appalachian field jumped suddenly upward following the application of the anticlinal principle to well location in the years following 1888. Important as was the part played by geology in the Appalachian field at that time, it was insignificant compared to its part in the California and mid-continental developments. Eastern operators have never utilized geologists to the extent Western oil men have. In the Oklahoma field there are probably today from 25 to 50 geologists to one employed in the Appalachian field, exclusive of college teachers who make occasional investigations.

It is to be hoped that geologists will eventually be employed in the Appalachian field to a much greater extent than at present, and, if so, it is likely that the influence of geology on the future of the field will be considerable. There are very few pools, even among those that have been producing for years, which can not be extended to include a number of additional wells, while large increases in production will be possible in some instances. New pools can be opened at many additional localities, though most of them will be small. Gas, especially, may be located at scores of points where none is now obtained. A material new production may be developed by systematic geological efforts along this line.

The extensions will result in part from the development of the more conspicuous anticlines and structural terraces, but to a greater extent from the development of minor features of structure. Although large areas have been mapped and contoured structurally in great detail, considerable tracts still remain unmapped in what may be termed the modern detail. Whenever such mapping is done, new and unsuspected structures will almost surely be discovered.

Non-structural factors should be given more attention than they have received in the past. Variation of texture and cementation are of the utmost importance and should be carefully considered. The presence and character of unconformities, changes in thicknesses of producing sands, variations in intervals, axial variations of non-symmetrical folds, and a multitude of other similar factors should be given detailed attention. Faults are not unknown, even in the flatter outlying portions of the oil field, and may prove favorable to oil rather than otherwise, as they have in certain Oklahoma pools. Igneous dikes occur in New York, southwestern Pennsylvania, and Kentucky; their influence, if any, should be determined. Cross-anticlines should be more diligently sought for. Elsewhere their intersections have given domes of high promise.

A proper application of geology to the Appalachian field should do much to maintain production. The cost would almost certainly be warranted by the results. Even if only a single additional productive well out of ten were to be secured as the result of geological studies, its output would usually pay for the investigation. In the Oklahoma field the number of successful wells has risen in some instances from 60 per cent to 90 per cent as a result of the application of geological advice, an increase of 50 per cent over the number of successful wells drilled without geological assistance. Similar results should be attainable in Pennsylvania.

It is not anticipated that large new pools will be found nor that the production will ever be materially advanced. Geology should, however, assist materially in sustaining production and in postponing the exhaustion of the field.

INFLUENCE OF DEEPER DRILLING

Depth of drilling will have an important influence on the future of the Appalachian oil field. Again and again the field has been given new life by the pushing of the drill to depths and sands previously unattainable. The first well was only 69 feet deep, and for some years the depth averaged but a few hundred feet. Then, as methods improved and as the demand for oil became greater, the depth was progressively increased—first to 1,000, then to 2,000, and finally to upward of 3,000 feet. Two wells have been carried to a depth of a mile or more; one 6,000 feet deep at West Elizabeth, near Pittsburgh, and another, known as the McDonald well, to a depth of 7,100 feet, in the southwestern corner of the State.[24]

With reasonable improvements in equipment and methods of drilling, there should be no insurmountable difficulty in sinking wells to depths of 8,000 to 10,000 feet and at a cost still under that of many of the rotary drilled wells of the Coastal Plain or other unsolidified or partly consolidated materials. The determining factor will be the amount of oil contained in the deep beds. If, from the preliminary testing, it is found to be abundant, there will be no lack of wells to bring it to the surface. In general, however, it is anticipated that there will be found a tendency toward more gas and less oil at great depths. The deeper beds have less water, and the oil will tend to occur in synclines rather than anticlines. It should be lighter and of a better quality than the oils near the surface.

Oil, however, will not be found beyond a certain depth, partly because of the limitations placed on it by incipient metamorphism, as evidenced by fixed-carbon ratios of over 65 or 70 where coals are present or by cumulation where coals are absent. What this depth will be is as yet unknown, but it may be as low as 5,000 or 6,000 feet even in areas remote from strong folding.

Of the deeper horizons, the so-called Clinton sand (Medina) appears to be the most promising. In central Ohio it yields gas freely in a broad belt along its upward tapering edge, and east of the gas belt it has afforded several oil pools, but it soon reaches a depth beyond the present limit of drilling. The fact that it is free from water suggests that the oil will follow the synclinal rather than the anticlinal method of occurrence, in which case there are fair prospects that it will be found in Pennsylvania and northern West Virginia. Its depth at the southwest corner of Pennsylvania has been estimated at about 8,000 feet, but for the most part it should be from 8,500 to 9,000 feet from the surface. It increases in thickness toward the east and may be less treacherous than in Ohio, but it seems probable that the metamorphic action referred to will limit production to considerably less depths.

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[24] Two wells, one in Pennsylvania and one in West Virginia, have been carried to equal or greater depths in 1917.

Whether or not drilling is extended to the Clinton, there is sure to be a gradual increase in depth of the wells in all the old fields, the tendency of which will be to sustain production and prevent the rapid decline characteristic of many other fields.

EFFECT OF IMPROVED METHODS OF RECOVERY

In late years a method of reestablishing in part the original conditions of pressure, etcetera, by pumping air back into the sand has been locally put in practice with promising results. If, through an extension of this method, the salt-water troubles can be overcome, or even materially reduced throughout any considerable portion of the field, the production should be noticeably increased and the life of the field prolonged.

EFFECT OF CHEAPER AND MORE EFFECTIVE REFINING METHODS

The lowering of refining costs or the extraction of greater percentages of gasoline will naturally delay the introduction of substitutes and will, therefore, like improved methods of recovery, tend to lengthen the life of the field. On the other hand, there would also be a tendency to lower prices, with a consequent retardation of development, as compared with what might otherwise take place. What the ultimate result upon the field would be is somewhat difficult to determine.

INFLUENCE OF POSSIBLE SUBSTITUTES

It is always within the range of possibility that, as petroleum becomes scarcer and the price of its products advances, some cheaper substitute, capable of being used in motor vehicles and gas engines, will be discovered. When the price of gasoline permanently reaches 30 to 35 cents a gallon it will be approaching the price at which alcohol may possibly be produced and marketed by large corporations. If such a substitute is introduced it will limit the demand and price obtainable for petroleum and will tend to restrict the production of the latter.

A more probable substitute for natural petroleum is likely to be the oil extracted from petroliferous shales. From the distillation of a ton of oil shale in Scotland is obtained 30 to 35 gallons of crude oil and 30 to 40 pounds of ammonium sulphate. Refining the oil results in the obtaining of 2 gallons of gasoline, 10 gallons of kerosene, and 7 gallons of lubricating or other heavy oils. The rest is paraffin and loss, the latter usually amounting to from 25 to 30 per cent.

At what price distilled oils will begin to take the place of natural oils will depend largely on price of labor, cost of machinery, and efficacy of methods. It is believed by some that the substitution is likely to occur when oil permanently reaches a price of $4 a barrel, though it may come either before or after this price is reached, according to the effect of extraneous factors. Temporary rises in price will have little or no effect.

TREND OF PRODUCTION CURVE

The Appalachian oil field practically reached its maximum production of 36,000,000 barrels per annum in 1891, continued with a production between 30,000,000 and 35,000,000 barrels until 1900, when it touched its second maximum of a little over 36,000,000 barrels. From this figure it has fallen off gradually to 24,000,000 barrels in 1914, a decline of 12,000,000 barrels in 14 years, during the last eight of which the output has remained nearly stationary. How long the present rate can be maintained is problematical, but the time is not likely to be long. The production has been better sustained in the Appalachian than in any other field, however, and the drop is likely to be comparatively slow. The decline after the output becomes less than 10,000,000 barrels per annum will normally be even slower. There is little doubt that the field will still be materially productive at the end of 50 years from today if outside factors do not intervene, although it is about 70 per cent exhausted.

Final Conclusions

While the structure may be said to be favorable to oil throughout the Appalachian field, from three-fourths to four-fifths of the producing horizons of the north end of the field are without representation south of West Virginia. Reservoirs in this area are few in number and poor in quality. The percentage of fixed carbon in coals is such that, if the postulated relation between it and the distribution of oil holds good, oil would not be likely to occur in any considerable amount in Kentucky, Tennessee, or Alabama, even if the stratigraphy and reservoir conditions were favorable.

Geology, if properly applied to developments, will materially assist in sustaining the production and prolonging the life of the field. The greatest promise of new supplies lies in deeper drilling. Better methods of recovery will help the field materially.

The normal life of the Appalachian field, if substitutes for petroleum are not introduced in the meantime, should be not less than 50 years more, but with slowly decreasing output. Production will never cease entirely; for, even if substitutes are found for illuminating and power purposes, there will still be a good demand for petroleum for lubricating, highway, and possibly fuel purposes. There is a probability, however, if other prolific fields are not discovered elsewhere, that the extraction of shale oil on a large scale will begin before the Appalachian field approaches exhaustion. If so, the active life of the field will be shortened.

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OIL FIELDS OF ILLINOIS [1]

BY FRED H. KAY

(Presented before the Society December 28, 1916)

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INTRODUCTION

After the discovery of the Illinois oil fields in 1905 it was but three years until the State had reached its maximum production of 33,686,238 barrels. From that amount a somewhat irregular decline has occurred, and in 1915 only 19,041,695 barrels were produced. For several years it maintained its rank as third in production until 1915, when the discovery of prolific fields in Texas forced Illinois into fourth place. The decline in production has been offset by the rise in value of the product. Up to the end of 1915 there had been produced from about 230 square miles in Illinois 251,368,311 barrels of oil, with a value of $201,053,017. The new fields that have been discovered in Marion, Clinton, and McDonough counties have not been able to overcome the normal decline in the output of Crawford, Lawrence, and Clark counties.

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[1] This paper is one of a series composing a "Symposium on the Geology of Petroleum." See this volume, p. 156.

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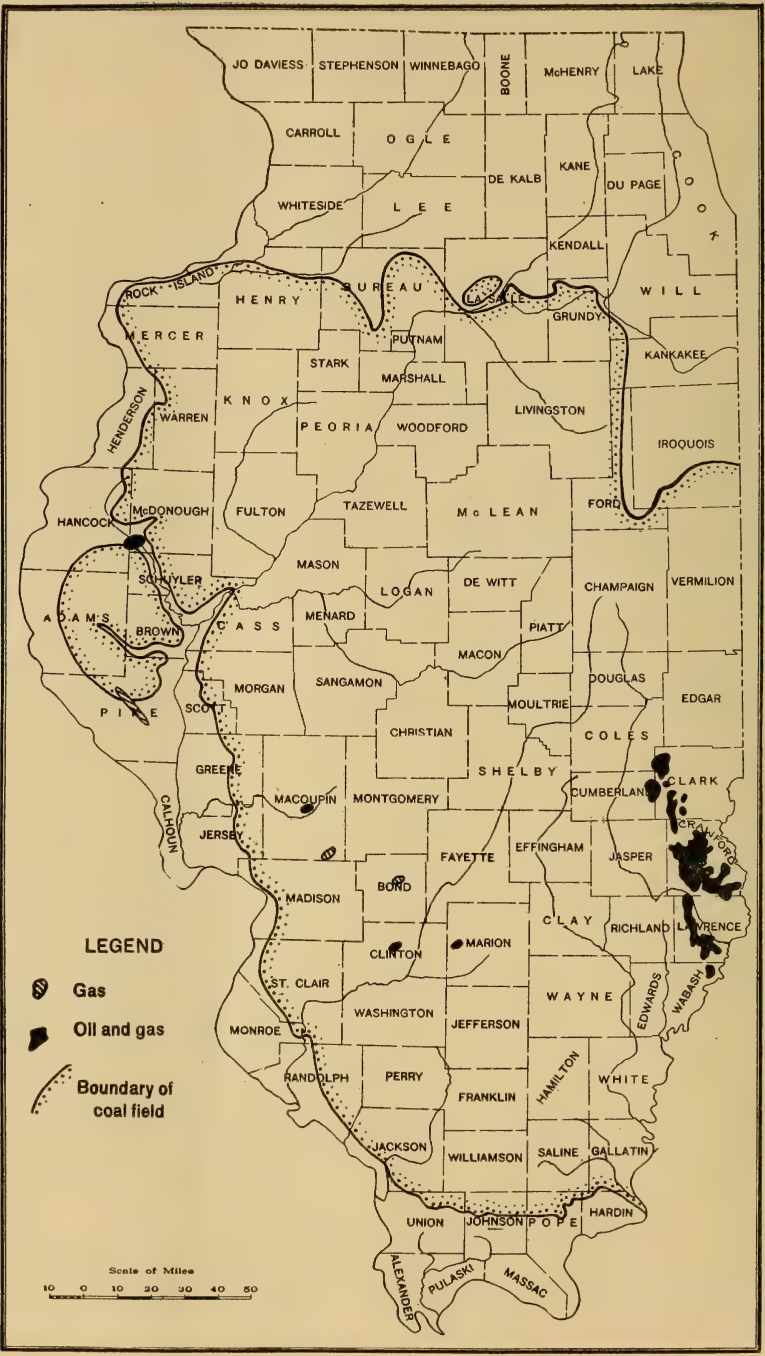
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KENDALL
ROCK ISLAND
BUREAU
LA SALLE
GRUNDY
WILL
HENRY
MERCER
PUTNAM
STARK
MARSHALL
KANKAKEE
KNOX
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WARREN
PEORIA
WOODFORD
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MASON
SCHUYLER
LOGAN
DE WITT
CHAMPAIGN
VERMILION
ADAMS
CASS
MENARD
BROWN
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SANGAMON
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SCOTT
CHRISTIAN
COLES
SHELBY
GREENE
CLARK
CUMBERLAND
MACOUPIN
MONTGOMERY
CALHOUN
CRAWFORD
JERSEY
EFFINGHAM
JASPER
FAYETTE
BOND
MADISON
CLAY
RICHLAND
LAWRENCE
CLINTON
MARION
LEGEND
Gas
Oil and gas
Boundary of coal field
ST. CLAIR
WAYNE
EDWARDS
WABASH
WASHINGTON
JEFFERSON
MONROE
HAMILTON
WHITE
RANDOLPH
PERRY
FRANKLIN
JACKSON
WILLIAMSON
SALINE
GALLATIN
HARDIN
UNION
JOHNSON
POPE
ALEXANDER
PULASKI
MASSAC
Scale of Miles
10 0 10 20 30 40 50

FIGURE 1.—*Map showing Location of Illinois Oil Fields in 1916*

STRATIGRAPHY

The producing sands in Illinois range in age from the top of the Carbondale formation of the Pennsylvanian series down to the upper part of the Trenton limestone. The latter formation produces in only one locality, at the north end of the Clark County field, at a depth of about 2,200 feet. Elsewhere in the State it has not yet proved to be commercially important. By far the greatest output is derived from the sandstones of the Carbondale and Pottsville formations of the Pennsylvanian, together with the Chester group and the Sainte Genevieve formation of the Mississippian. A sandstone at the base of the Niagaran produces in one small locality at Colmar, McDonough County, in western Illinois.

All of the producing beds are sands of variable thickness and character with the exception of the so-called McClosky sand, which is in reality the oolitic Sainte Genevieve limestone lying immediately beneath the Chester group. Of all the producing beds in the State, those of the Chester are the most regular in their development. The sands of the Pennsylvanian are extremely irregular in thickness and character, and it is often impossible to correlate them from one well to another with any degree of success. The Hoing sand, lying at the base of the Niagaran in the Colmar field, is the most restricted in its development of any producing horizon in the State. It appears to have been deposited in depressions on the Maquoketa surface during the encroachment of the Niagaran sea, but outside of the small area at Colmar numerous drill-holes in the western part of Illinois have failed to disclose its presence, and it does not seem to exist in the main fields of Clark, Crawford, and Lawrence counties.

The producing sands pinch out to the north along the La Salle anticline, due in all probability to the existence of the anticline previous to the deposition of the oil-bearing beds. The important Chester group is present only in the southern one-third of the State. Consequently production outside the area shown must come from the Pottsville, the Niagaran, or the Trenton.

STRUCTURE

GENERAL STRUCTURE OF STATE

Structurally the State is a spoon-shaped basin, the tip lying in the northwest corner and the deepest part of the bowl in Wayne, Edwards, Hamilton, and White counties, in the southeast corner of the State. The long axis of the spoon extends northwest-southeast, parallel to the main oil fields. In the west and central parts of the State the dip toward the axis of the basin is commonly as low as 10 feet per mile. The westward dip from the main fields to the basin is much more pronounced, and the same is true for the beds at the southern and the southwestern rim of the basin. East of the main oil fields of Crawford and Lawrence counties the strata rise gently into Indiana. At the southern end of the State diastrophism has been exceptionally active and the resulting structural conditions are unusual for Illinois. Strong folds and faults are numerous and in places igneous intrusion has occurred.

The main irregularity in the general structure is the La Salle anticline, which extends northwest-southeast through the eastern part of the State. Not only is this anticline asymmetrical, but its axis plunges toward the southeast.

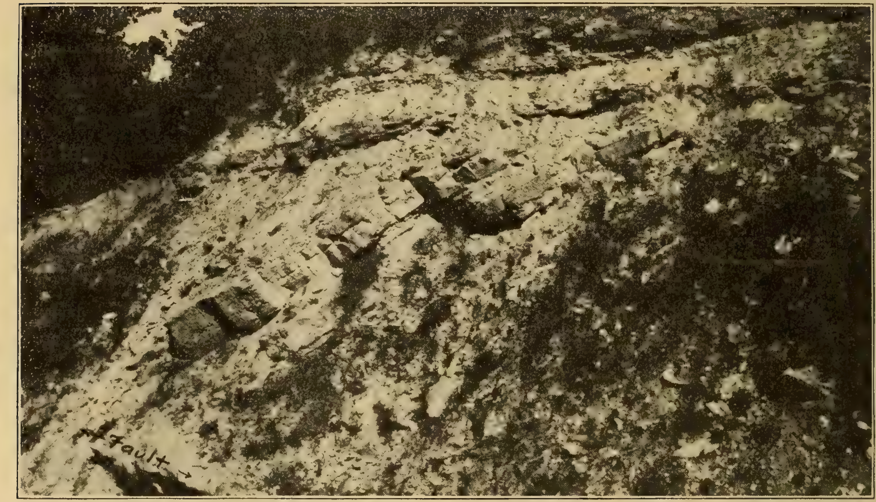


FIGURE 2.—*Unconformity between the Chester and Pottsville Formations*

Two miles south of Pomona, Illinois. (From Bulletin 35, Illinois Geological Survey)

The Duquoin monocline is the most conspicuous modification of the structure in the western part of the State. The fold is clearly marked from the Sandoval oil field southwest to the town of Duquoin, where it turns more westward and is traceable into Jackson County. West of the axis the beds lie almost flat, with slight dips north and northwest, whereas for some distance east of the axis the eastward dip is 300 feet per mile.

PERIODS OF DIASTROPHISM

Several distinct periods of folding have occurred in different parts of the State, but it has usually affected the same lines of weakness. At La Salle the evidence is clear that a period of diastrophic action followed the Trenton and was probably coincident with the formation of the Cincinnati arch. Further uplift along the La Salle anticline occurred in post-Pennsylvanian, pre-Pleistocene time, and it is possible that movement was effective even during Coal Measures time.

In southwestern Illinois it is clear that some folding took place after the deposition of the Chester and prior to Pennsylvanian time. The early existence of the La Salle fold appears to be responsible for the thinning out of the producing sands to the north along the axis of the anticline. Considering the different periods of folding and regional uplifts, it is fortunate that work on surface rocks has disclosed satisfactorily the existence of small folds affecting beds as low as the Maquoketa.

The important diastrophism prior to that time renders impossible any accurate determination of Trenton structure from surface work except along the major structural features.

RELATION OF FIELDS TO STRUCTURE

The main oil fields of Clark, Crawford, and Lawrence counties lie at the southeast end of the plunging La Salle anticline, on the east side of the Illinois basin. The other fields of the State occupy isolated positions along the gentle eastward dip in the western part of the State.

Conditions affecting Accumulation

THE LA SALLE ANTICLINE

Broadly considered, accumulation has taken place in the main oil fields at the southeast end of the plunging La Salle anticline. The dip of the beds to the southeast along the axis of the anticline is well illustrated by the fact that the lowest producing horizon—namely, the McClosky "sand" of the Sainte Genevieve limestone—lies within 350 feet of the surface at the northwest end of the Clark County field, whereas in the Lawrence County district it ranges in depth from 1,700 to about 1,860 feet. That this sand does not produce throughout the length of the field is probably due to local irregularities in structure and to the variable nature of the producing bed. It ranges from 2 to 10 feet in thickness and averages not more than 10 feet over the entire field. Besides, instead of being a single bed, it is probably a zone in the upper part of the Sainte Genevieve formation, the position of the oil being controlled by the porosity of the rocks. Within the zone, which has a maximum reported thickness of 80 feet, one to three oil-bearing horizons are reported.

Above the McClosky oil sand six other sands produce in the main oil fields of the State. No sand is everywhere present in such thickness and condition as to be oil bearing. For each sand, then, the general result is a development here and there at the same horizon of lenticular masses of sand capable of acting as reservoirs for oil and gas, surrounded by beds which are now impervious to the movement of these materials. In a broad sense, accumulation is controlled by the anticlinal structure, but has taken place independently in the different lenses of each sand. Otherwise it would be difficult to understand the existence of salt water along the axis of the anticline in positions considerably higher than oil in the same sand in other parts of the anticline or further down the axis in the same sand.

The asymmetrical nature of the La Salle anticline has caused the main oil fields to be limited much more closely on the west side than on the east. On the west side all of the producing sands are carried beneath the level of permanent salt-water saturation along a rather definite line. The sands of Lawrence County show abundant water along the flanks of the anticline and but little through the center of the field, except in the lower Bridgeport and Buchanan sands of the Pottsville. These rocks contain large quantities of water over the entire Lawrence County area, whereas farther north, along the axis of the anticline, in Crawford County, water is not a disturbing feature except at the edges of the field. For this reason it appears that there is probably a better lateral connection between the different lenses of the Pottsville rocks than exists between the separated porous portions of the lower sands.

ISOLATED POOLS ON EAST-SIDE ANTICLINE

On the east side of the La Salle anticline are a number of small isolated pools which are of more than ordinary interest to the geologist because of their possible mode of origin. Two of these pools—the Flat Rock and Birds—have their longer axes parallel to each other in a northeast-southwest direction almost at right angles to the axis of the La Salle anticline. For this reason, before detailed studies were made in the field, it was supposed that the accumulation in the smaller pools to the east was controlled by small cross-anticlines, and that the existence of other similar structural folds might be determined by geological work on surface outcrops. Recently Dr. John L. Rich has made careful studies of the problem in connection with field-work on the Birds and Vincennes quadrangles, in cooperation with the United States Geological Survey, and the writer is indebted to Doctor Rich for much material. The four principal productive pools on the east side of the anticline are the New Hebron, Flat Rock, Parker, and Birds, and they are almost, if not entirely, separated from each other. The principal characteristic of each pool is the presence of a thick, continuous bed of sand which thins out, or becomes lenticular, along the edges of the pool. Between the productive pools the sands are either very thin or entirely absent. Besides the larger productive pools, there are a number of smaller pools which lie at about the same level as the larger pools, but are entirely distinct from them, or are connected with them by thin, unproductive beds of sand which are thinner and lower than the productive beds in either the larger or the smaller pools. In all the producing pools in the east side of the axis of the La Salle anticline the sand lies at approximately the same elevation above sealevel. It has not been possible to detect with certainty any folding which may account for the location of the productive pools. Any differences in elevation due to folding of the strata are without doubt less than the known differences in elevation due to the irregularities in the sand lenses. Another feature which appears to have a direct bearing on the origin of the sands is that in the smaller sand masses there is commonly a tendency to cut down into the underlying beds and to present a convex surface downward, whereas the large sand masses which compose the Birds, Parker, and Flat Rock pools have their surfaces convex upward.

MODE OF ORIGIN OF THE SANDS

It is of the utmost importance that the mode of origin of the sands responsible for the accumulation of oil shall be known before any attempt is made to locate new favorable territory or the possible extension of older fields, such as those of Crawford County. After a careful consideration of all possible conditions governing the deposition of the Robinson sand, Doctor Rich reaches the conclusion that these sands may be part of a great delta formation in which are combined river-channel deposits, offshore sand-bars thrown up by the waves along the front of the delta, and wave-worked sands spread out over the adjacent ocean bottom. Rich writes:

> "The present deltas of the earth, where exposed to wave action, are much modified along their margins by the waves. The materials supplied by the rivers are picked up and strewn along the coast by waves and currents and built up into sand-bars which differ, however, from typical offshore bars in that they are smaller and more irregular, and, furthermore, in that the constant building out of the delta front causes new bars to be thrown up at intervals outside the older ones, thus producing a more or less parallel series of discontinuous sand-bars, the inner and older of which are protected from wave erosion and, in the normal course of events, are finally buried under delta deposits and are preserved intact. On the modern deltas irregular shifting of the distributary streams constantly alters the form of the delta front; incloses lakes here and there by building out irregularly; fills others with sand, and gives rise to numerous channel deposits in the upper beds of the delta.

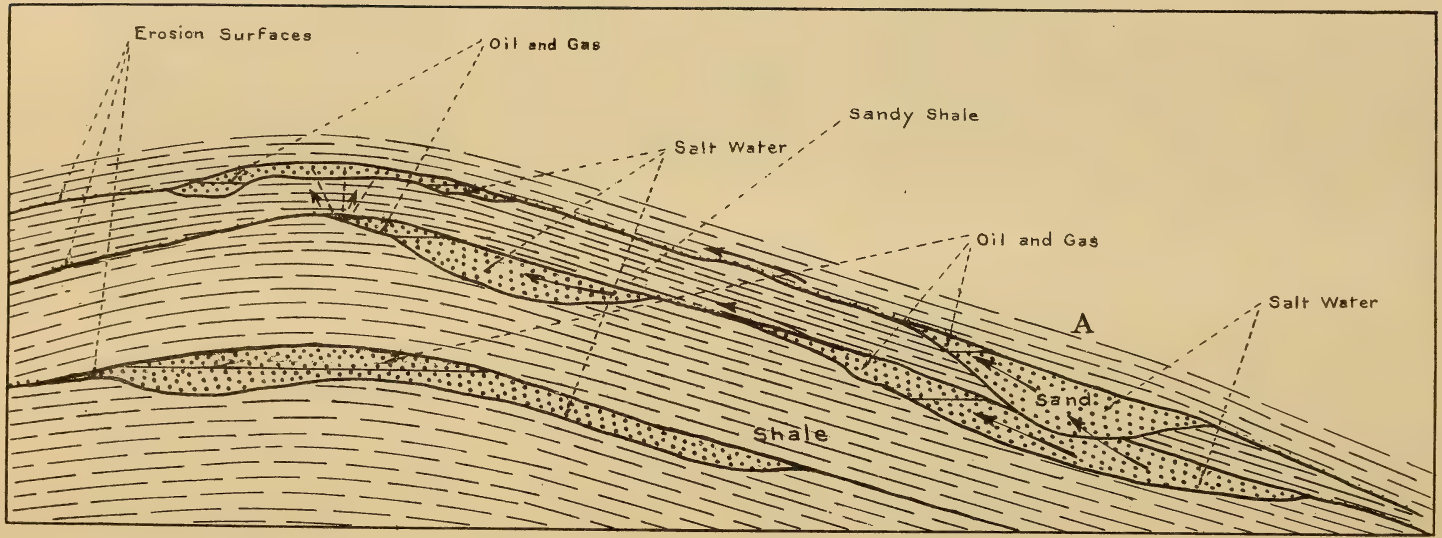

Erosion Surfaces
Oil and Gas
Sandy Shale
Salt Water
Oil and Gas
Salt Water
A
Sand
Shale

FIGURE 3.—*Idealized Section through a Dome*

Showing sand-filled channels in cross-section, points of accumulation of oil and gas, and direction of migration. From Bulletin 31, Illinois Geological Survey, in cooperation with U. S. Geological Survey.

> "Thus on modern deltas are found in appropriate proportion all the features described as characteristic of the Robinson sand, as determined from the well records. Such an explanation harmonizes the barlike form of the larger sand masses with the channel features and the irregularity of certain of the smaller pools and with the even, thin sand-beds of some of the outliers. According to this explanation, the Flat Rock and Parker pools are sand-bars probably of the same age; the Birds pool is a larger bar parallel to the first and built presumably at a later time farther offshore. The smaller and more irregular pools may be river-channel deposits, portions of a delta top or front; smaller, more irregular bars, or lagoons that the delta deposits formed opposite the mouths of tidal inlets."

The clear-cut boundary of the sand masses on the southeast side and the outfingering lenses toward the northwest seem to bear out the belief that the open sea lay to the southeast and the land to the northwest in Upper Pottsville time.

If this hypothesis is correct, the prediction of any extension eastward of the Crawford County fields becomes extremely hazardous. There are untested areas fully as large as any of the producing pools mentioned above, but in most of these untested areas there is absolutely no surface indication upon which the geologist may base a prediction as to the existence of favorable structure, much less predict the presence or absence of sands capable of holding oil. In order to offset the disadvantage under which the geologist works, the Illinois Geological Survey has published a map which shows the location of all dry holes that have been drilled deep enough to test the Robinson sand. Thus attention is called to the areas which yet remain to be tested.

HEAVY OIL IN FLAT ROCK POOL

In parts of the Flat Rock pool the presence of oil of 19° Baumé gravity, as compared with much lighter oils in other parts of the same sand in Crawford County, has given rise to much speculation as to its cause. Recent detailed studies of the well records seem to show that in most cases where the heavy oil exists there is present above the regular oil sand a higher lenticular mass of sand which has a direct connection with the underlying oil sand. In practically all cases the upper lens is filled with gas, which suggests that the lighter materials have been given an opportunity to escape from the regular oil sand, and that the gravity of the oil which remains is dependent on the extent to which this action has taken place. Heavy and light oils occur in the same sands and in the same pool, but in all cases they seem to bear a definite relation to the existence of the higher lenses as mentioned above.

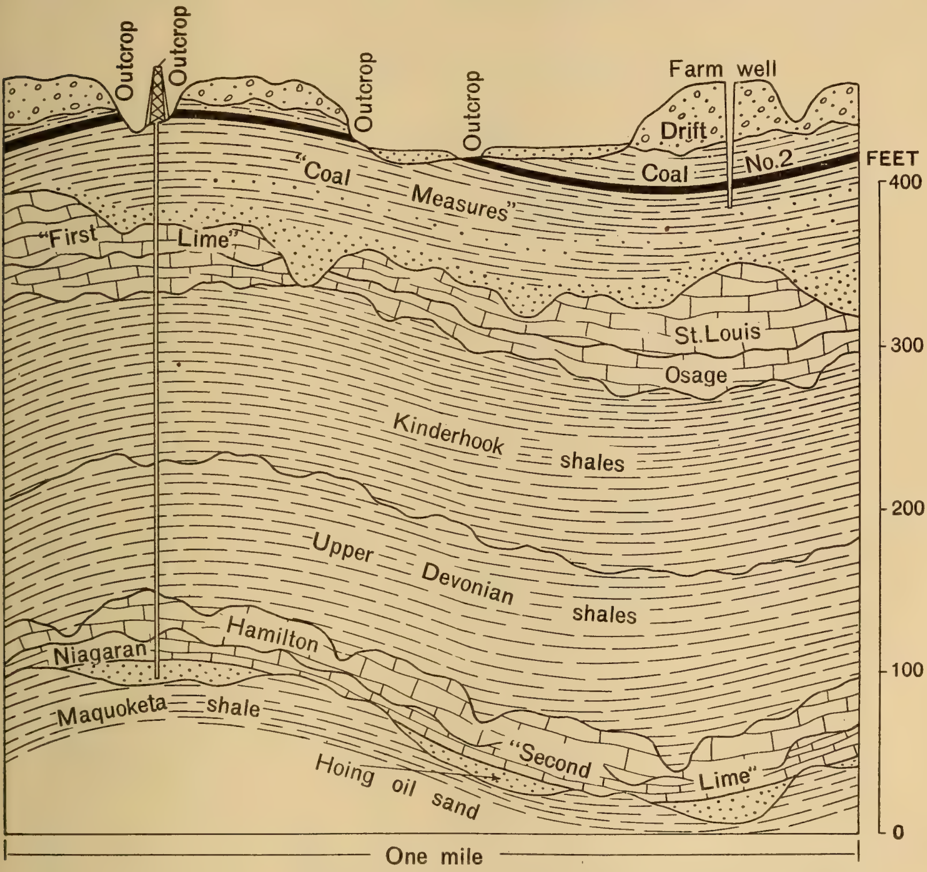
THE COLMAR FIELD OF WESTERN ILLINOIS

In the bottom of the Illinois basin and well up on its sides the Pottsville rocks are completely saturated with salt water. In the western-central part of the State, however, a few isolated small domes produce commercial quantities of gas and smaller quantities of oil. Of these, the Staunton gas field, the Carlinville oil and gas field, and the old Litchfield oil and gas field are the most important. In these fields the oil and the gas do not occur in continuous sandstone bodies, but are found in sandstone lenses which are locally discontinuous. As many as four productive horizons have been recognized, separated by a small vertical interval. Theoretically, a tilted, porous sandstone lens should provide conditions for accumulation of oil and gas at its upper end; but in Illinois the bedding planes of the Pottsville do not seem to be impervious enough to prevent the lateral movement of oil and gas unless doming of the strata has capped the edge of the porous bed and effectually prevented the escape of the oil. At the top of a dome affecting several sandstone lenses accumulation will tend to take place independently in each lens, as shown in figure 3, which is a reproduction from a report by Wallace Lee for the State Geological Survey, in cooperation with the United States Geological Survey.

Since it is impossible in any given area to predict the presence of a porous bed in advance of drilling, it is practical in western Illinois merely to point out the presence of structural domes which may or may not be underlain by beds capable of acting as reservoirs for oil and gas. This method has been successful in locating the only producing fields in western Illinois—namely, the Staunton, the Spanish Needle Creek, and the Colmar fields.

Great interest has been manifested in the extreme western part of the State since the discovery of oil at the base of the Niagaran at Colmar. The existence of a dome was first pointed out by Henry Hinds from levels run to coal number 2, which outcrops at the surface. Commercial oil was found in a sandstone which was probably deposited in depressions on the Maquoketa surface during the encroachment of the Niagaran sea. Therefore the sand exists as lenses separated by areas in which the limestone lies directly on the shale with no intervening sand. No direct connection is apparent between the Hoing pool, where the sand lies 90 feet above sealevel on a terrace at the northeast side of the dome, and the Hamm pool on top of the dome, where the sand is 70 feet higher. Likewise, the pool at the town of Colmar lies on the north side of the dome and probably has no direct connection in the sand with either of the other pools.

In contrast to the porous nature of the bedding planes in the Pottsville rocks mentioned above, the contact of the Niagaran limestone with the Maquoketa shale where the sand is absent appears to be impervious, and for this reason accumulation of oil and gas takes place in each lens independently. The lower part of the sand on the terrace at the northeast side of the dome is filled with salt water, as is also the portion of the dome farther down the dip, but the lens of sand at the top of the dome also has its proportion of salt water, which lies about 70 feet higher than that on the terrace.


Outcrop
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Drift
Coal
No.2
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"First
Lime"
St. Louis
Osage
Kinderhook
shales
Upper
Devonian
shales
Hamilton
Niagaran
Maquoketa
shale
"Second
Lime"
Hoing oil sand
FEET
400
300
200
100
0
One mile

FIGURE 4.—*Sketch showing Significance of Unconformities and the "spotty" Character of Sand in Colmar Area*

A number of domes equal in magnitude to that at Colmar have been located in the western part of Illinois, but outside of the Colmar area no sand has been found at the base of the Niagaran. Many of the wells drilled outside of the present producing field have developed small quantities of oil at the contact of the Niagaran with the Maquoketa, but in the absence of a proper reservoir no other commercial accumulations have been discovered. Practical exploration demands that all the domes in the western part of the State be located and tested in the hope that the combination of favorable structure with porous beds may somewhere be disclosed.

CONTENT OF OIL PER ACRE

Recent careful planimeter measurements show that Illinois has at present approximately 230 square miles of producing oil territory. Up to the end of 1916 it has produced about 1,830 barrels of oil per acre.

It is difficult to secure accurate figures concerning the actual production from a given sand. In general, however, despite the fact that the Illinois sands are extremely variable, some of them attaining a thickness of more than 100 feet in places, the producing part is generally but a small per cent of its total thickness. The different lenses of the Robinson sand in Crawford County average about 25 feet in thickness, whereas the "pay" sand and averages only about 7 feet. In two of the pools the sand ranges from 25 to 40 feet and is saturated with oil throughout, but this condition is exceptional.

The following figures are furnished through the kindness of the Ohio Oil Company. They represent the total production per acre to January 1, 1917, of typical farms underlain by the different producing sands of Illinois:

Total Production per Acre for typical Areas, Illinois Sands

Sand	Depth	Period, years	Barrels
Casey	350	10	5,309.93
Casey	350	10	2,919.37
Robinson	900[2]	9	719.14
Bridgeport	800–1,150	9	8,390.49
Buchanan	1,150–1,350	10	36,233.98
Kirkwood	1,350–1,650	9	2,546.22
McClosky	1,750–2,000	8	15,672.80

Many farms in the Lawrence County field produce from the four last-mentioned sands, and at the same rate would have produced to date more than 60,000 barrels per acre, a figure that becomes especially interesting in view of the fact that the field will be active for many years.

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[2] Average thickness, 7 feet.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 28, PP. 667-676 SEPTEMBER 30, 1917

PETROLEUM IN OHIO AND INDIANA[1]

BY J. A. BOWNOCKER

(Presented before the Society December 28, 1916)

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Mississippian and Pennsylvanian sands as sources of petroleum in Ohio and Indiana.......... 674

INTRODUCTION

The earliest date of man's knowledge of the presence of petroleum in the rocks of Ohio and Indiana is unknown. In places a film of oil was observed floating on the surface of streams; occasionally it was observed in water wells, and drillers for salt occasionally found it to their sorrow, for the smell was thought to be injurious to the salt.

Thus, as early as 1819, or forty years before the Drake well, Dr. S. P. Hildreth, one of the pioneer geologists of Ohio, reported that petroleum had been found in a salt well at a depth of more than 400 feet, in the Little Muskingum Valley. While the eruptions of this well interfered with salt-making, the oil afforded "considerable profit" and was "beginning to be used for lamps, in workshops and manufactories." "It affords," said Dr. Hildreth, "a clean, brisk light when burnt this way, and will be a valuable article for lighting the street lamps in the future cities of Ohio."[2]

The discovery by Colonel Drake, on Oil Creek, in 1859, set the drill to work at many places, and among these was the valley of Duck Creek, in

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[1] This paper is one of a series composing a "Symposium on the Geology of Petroleum." See this volume, p. 156.

Manuscript received by the Secretary of the Society February 12, 1917.

[2] Am. Jour. Sci. and Arts, vol. x, p. 5.

Washington County, Ohio. There, late in 1860, oil was found at a depth of 59 feet, and this marks the real beginning of the petroleum industry in Ohio. The oil from this pioneer well had a density of 28° Baumé and commanded as much as $28 per barrel. Other wells were drilled in eastern and southeastern Ohio about the same time and the tools have not been quiet for long periods since that time. As early as 1862 drilling was done for petroleum in Crawford County, Indiana, but only a trace of oil was found and wells which were sunk in different parts of the State about that time gave similar results.

PRINCIPAL OIL-PRODUCING ROCKS IN OHIO AND INDIANA

The principal oil-producing rocks are:

Pennsylvanian..........	Mitchell sand (Ohio). Macksburg 140-foot, or first Cow Run, sand (Ohio). Macksburg 500-foot sand (Ohio).
Mississippian...........	Huron sandstone[3] (Indiana). Keener sand (Ohio). Big Injun sand (Ohio). Berea sand (Ohio).
Devonian...............	"Corniferous" limestone (Indiana).
Silurian................	"Clinton" sand (Ohio).
Ordovician.............	Trenton limestone (Ohio and Indiana).

The second great event in the petroleum industry of Ohio and Indiana was the discovery of oil in the Trenton limestone at Findlay, Ohio, in 1885, and in Wells County, Indiana, in 1890.[4]

THE TRENTON LIMESTONE FIELD IN OHIO AND INDIANA

The discovery at Findlay, referred to in the preceding paragraph, soon started the drill at work in every county in western Ohio and eastern Indiana. A result was a large production of a dark, strong smelling oil, unpopular with both producer and refiner and for which there was an unwilling market. Not only did the oil appear to poor advantage in comparison with that of Pennsylvania, but it had a pungent odor due to the sulphur compounds. The density of the oil usually varied between 36 and 42° Baumé, and it was therefore heavier than the Pennsylvania oil. Moreover, the source also of the oil was prejudicial, for drillers and operators had little regard for an oil that came from a limestone. However, the yield of oil increased rapidly, so much so in fact that the Standard Oil Company had difficulty in storing it. To discourage further production, this company reduced the price several times, until in 1887 it was listed at only 15 cents per barrel. Conditions incident to the discovery of petroleum in the Trenton limestone field of Indiana were similar to those of Ohio. While the wells of the field have not equaled in size many of the great wells of the Far West and Southwest, one at least was secured which, after flowing over the derrick top during forty-eight hours, produced at the rate of 10,000 barrels per day.[5]

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[3] Edward Barrett: Dept. of Geol. and Nat. Res. of Indiana, 39th Ann. Rept., p. 18.

[4] Ibid., 38th Ann. Rept., p. 10.

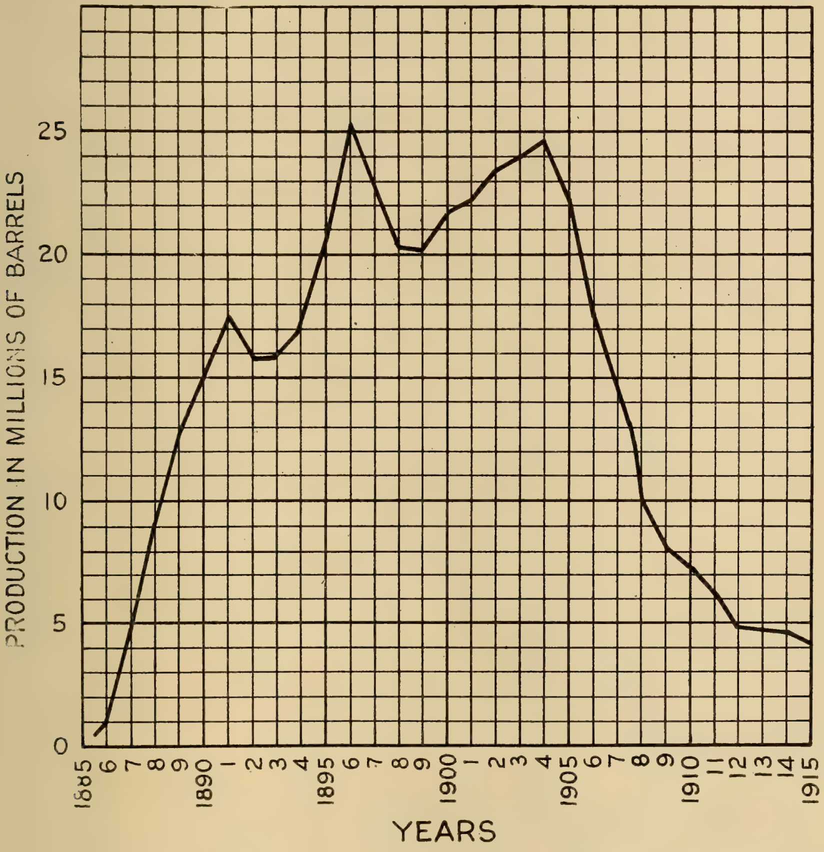

FIGURE 1.—*Production of Trenton Limestone Oil Field in Ohio and Indiana from 1885 to 1915*

Gradually the producers and refiners raised their estimates of the Trenton oil, and of course an advance in price and an increase in production followed. In 1896 the output from the Trenton field in Ohio attained its maximum and exceeded 25,250,000 barrels. The maximum production was not reached in Indiana until 1904, when the yield was in excess of 11,300,000 barrels. How far these States have passed the zenith of their production from this rock is shown by the fact that in 1914 the yield from Ohio was only 3,700,000 barrels and from Indiana 1,300,000. The drill, however, is at work in both States and in 1915 1,262 wells were sunk, of which nearly 1,100 were rated as producers. The initial yield of these, however, was small and more old wells were abandoned than new producers secured. Doubtless the proportion of abandoned wells will increase from year to year, and yet the end of the Trenton field is not in sight. The magnitude of the drilling is shown by Barrett's statement that 30,000 Trenton wells have been drilled in Indiana, and doubtless the number in Ohio is much larger. The productive territory extends in a disconnected manner from Lake Erie, east of Toledo, southwest like an arc of a circle to Marion, Indiana, a distance of approximately 150 miles. In width the range is great; in places it is sufficient for only a few rows of wells, while elsewhere it may be 20 miles.

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[5] Geol. Survey of Ohio, 4th ser., Bull. 1, p. 62.

The rock succession is shown by the following well records:[6]

OHIO

	Thickness Feet
Drift	8
Niagara limestone	167
Niagara shale and Clinton limestone	108
Medina shale	47
Hudson River shale and limestone	462
Utica shale	300
Trenton limestone at	1,092

INDIANA

	Thickness Feet
Drift	50
Niagara limestone	153
Hudson River limestone	451
Utica shale	300
Trenton limestone at	954

So regular are the formations that these well records can be duplicated by the thousand, though there is considerable variation in the depth of wells due to their position with reference to anticlines. In the Ohio fields the depth to the Trenton usually ranges from 1,000 to 1,500 feet, but in Indiana the depth is more uniform and, according to W. S. Blatchley, averages 1,000 feet. The principal "pay rock" usually lies within 50 feet of the top of the Trenton, and in early days in the Ohio part of the field it was a general belief among drillers that unless oil was found by

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[6] Edward Orton: Geol. Survey of Ohio, vol. vi, p. 112.
W. S. Blatchley: Indiana Dept. of Geol. and Nat. Res., 1897, p. 68.

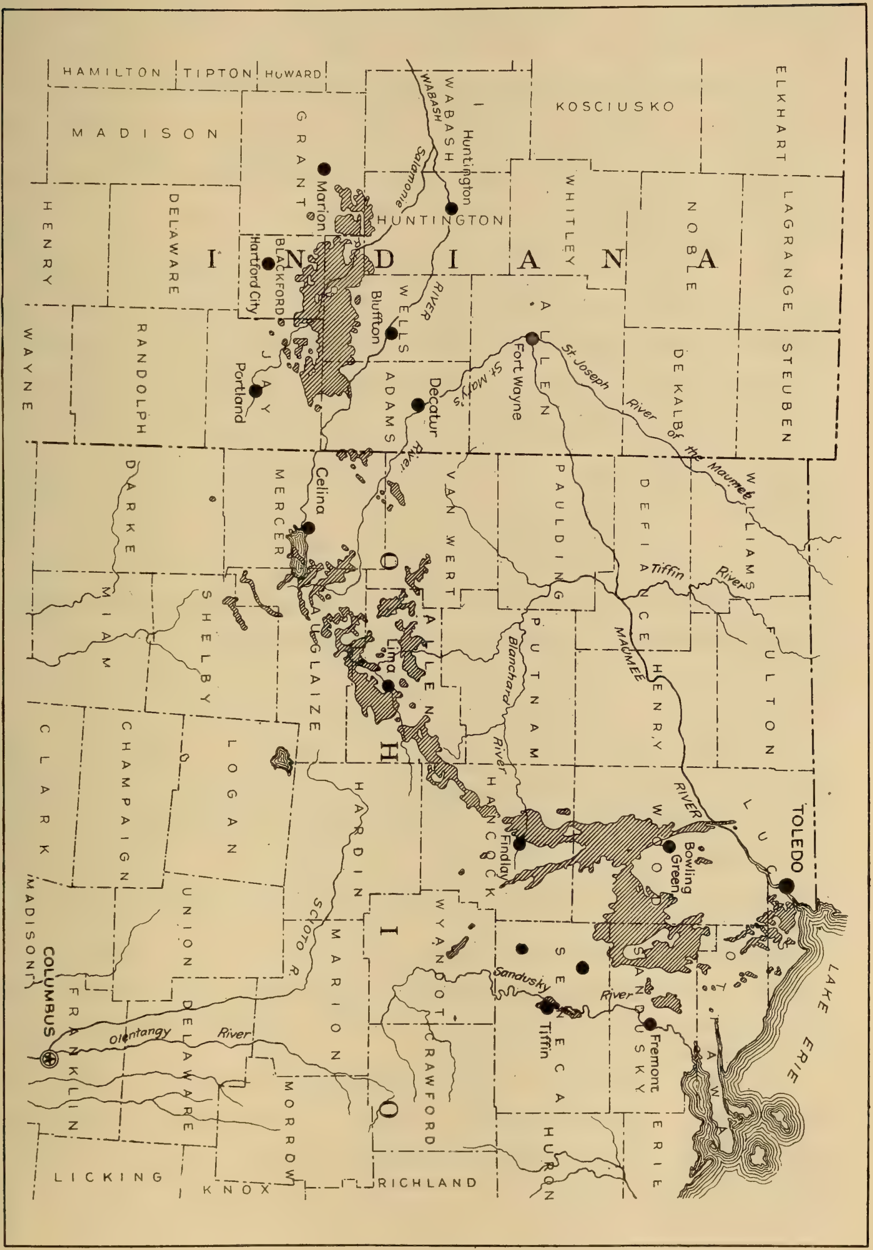
INDIANA
OHIO
HAMILTON
TIPTON
HOWARD
MADISON
GRANT
WABASH
KOSCIUSKO
ELKHART
LAGRANGE
NOBLE
WHITLEY
HUNTINGTON
HENRY
DELAWARE
BLACKFORD
WELLS
ALLEN
DE KALB
STEUBEN
WAYNE
RANDOLPH
JAY
ADAMS
DARKE
MERCER
VAN WERT
PAULDING
DEFIANCE
WILLIAMS
FULTON
HENRY
PUTNAM
ALLEN
AUGLAIZE
SHELBY
MIAMI
CLARK
CHAMPAIGN
LOGAN
HARDIN
HANCOCK
WOOD
LUCAS
OTTAWA
SANDUSKY
SENECA
WYANDOT
MARION
UNION
MADISON
FRANKLIN
DELAWARE
MORROW
CRAWFORD
HURON
ERIE
LICKING
KNOX
RICHLAND
Marion
Huntington
Hartford City
Portland
Bluffton
Decatur
Fort Wayne
Celina
Lima
Findlay
Bowling Green
TOLEDO
Tiffin
Fremont
COLUMBUS
Wabash
Salamonie
RIVER
St. Mary's
St. Joseph
River
River of the Maumee
Tiffin River
MAUMEE RIVER
Blanchard River
Sandusky River
Scioto R.
Olentangy River
LAKE ERIE

FIGURE 2.—*The Trenton Limestone Oil Field in Ohio and Indiana*

the time the drill had penetrated 50 feet of the limestone it was useless to continue work. Later, however, a second and even a third "pay" was found, but these have proven of small value in comparison with the first.

The Trenton limestone in the Ohio part of the field, at any rate, is dolomitic, two analyses showing from 33 to 43 per cent of magnesium carbonate. The rock usually has a dark gray color and, true to its composition, has a marked porosity. Morever, many samples hurled to the surface in shooting wells contain frequent holes, doubtless due to the solvent action of the contained water.

The structure of the Trenton limestone in these two States has a marked relation to the production of oil. As has long been known, the Cincinnati axis crosses the Ohio River a short distance east of Cincinnati. Following it northward from that place, it is soon found to bifurcate, one arm running northwest toward the south end of Lake Michigan, and the other one east of north toward the west end of Lake Erie.[7] In other words, the axis forms a Y with the stem crossing the Ohio River near Cincinnati. In Ohio, part of the richest territory has been found on this arch, but in Indiana it does not appear on the summit of the arch, but on the north side, where the rock dips to the northeast. The Trenton limestone everywhere in these two States contains an ocean of brine, and this naturally forced the oil to the higher places.

THE "CLINTON" SAND FIELD IN OHIO

This field lies entirely in Ohio and consists of a number of comparatively small pools that extend from Vinton County on the south to Wayne County on the north. Natural gas was discovered in this rock at Lancaster in 1887, and the drill has extended the reservoir so that it now extends in a disconnected manner from the shore of Lake Erie south almost to the Ohio River. Oil producers argued that where gas existed in such abundance oil must be near, and they at once began the search. Oil in paying quantities was first gotten in this rock in 1899, but no large pools were found until in 1907, when the reservoir in eastern Fairfield County was located.

While the producing rock is known as the "Clinton," it usually lies from 100 to 150 feet below the limestone of that name and appears to form a part of the Medina formation.[8] It commonly has a light color, but in places is brick red. The rock is patchy in nature, so that the driller can not be certain of finding the sand when he reaches its position.

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[7] Edward Orton: Geol. Survey of Ohio, vol. vi, p. 46.
E. P. Cubberly: Geol. and Nat. Hist. of Indiana, 18th Ann. Rept., p. 221.

[8] J. A. Bownocker: Econ. Geol., vol. vi, p. 37.

Interesting to report, the sand does not exist west of the longitude of Columbus, and there its place is taken by shales. In thickness the sand generally varies from a few feet to 100, but the usual range is from 10 to 40. The wells ordinarily vary in depth from 2,300 to 3,500 feet.

Record of a "Clinton" Well near Bremen, Fairfield County, Ohio

		Thickness *Feet*	To bottom *Feet*
Mantle rock		49	49
Cuyahoga and Sunbury sandstone and shales		626	675
Berea sandstone		35	710
Bedford and Ohio shales		975	1,685
Devonian limestone		50	1,735
Silurian	Monroe limestone	275	2,010
	Niagara limestone	360	2,370
	Clinton limestone	95	2,465
Shales		120	2,585
"Clinton" sand		34	2,619
Bottom of well		....	2,620

The oil, which has a density varying from 35 to 46° Baumé, differs in no important way from the light oils of Pennsylvania and West Virginia. Its occurrence is unique in Ohio, in that it appears to be free from water. From this fact the conclusion is reached that the oil lies in shallow basins rather than on the slopes of anticlines. The production of the "Clinton" sand at its maximum was about 1,300,000 barrels per year. Efforts have been made within the past few years to extend the "Clinton" sand field, but without notable success. The great depth of the sand and its treacherous nature make the search a very costly one.

"Corniferous" Rocks as a Source of Petroleum in Indiana

Rocks of Corniferous age are not a source of oil in Ohio and not a large source in Indiana, but the Phœnix well, which was drilled in Terre Haute in 1889, is the best producer ever drilled in that State.[9] The "Corniferous" limestone[10] was struck at a depth approximating 1,660 feet, and for at least twelve years the production averaged 1,000 barrels of oil per month. In 1908 it yielded 15 barrels per day. Few wells in this country have so large a daily yield after twenty-seven years' continuous production. Other wells were, of course, sunk in this locality, but they were all failures. Later a few small producers were secured in the "Corniferous," south and southeast of Terre Haute, but were it not for the remarkable Phœnix well the field would not be mentioned.

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[9] W. S. Blatchley: Dept. of Geol. and Nat. Res. of Indiana, 25th Ann. Rept., p. 517.

[10] Some geologists call this oil rock sandstone.

MISSISSIPPIAN AND PENNSYLVANIAN SANDS AS SOURCES OF PETROLEUM IN OHIO AND INDIANA

The Mississippian sands rank among the most important sources of oil in Ohio, and their value is rising in Indiana. The producing counties in Ohio extend from Trumbull on the north to Washington on the south, or, in other words, almost entirely across the eastern part of the State, but Monroe and Washington have been by far the largest producers. The pools, while numerous, are mostly small and not more than 2 or 3 include more than 10 square miles. The number of wells drilled is very large and may be counted by the thousands. Condit estimates the wells drilled in the Woodsfield quadrangle alone at about 2,000.[11] So extensively has testing been done that the chances of discovering large reservoirs are very small, and the production of 5,586,433 barrels in 1903 will probably stand as the maximum.

The following composite well record from Washington County shows the principal oil sands and their relative positions in eastern and southeastern Ohio:

	Thickness *Feet*	To bottom *Feet*
Pennsylvanian:		
Mantle rock	10	10
Meigs Creek coal	5	15
Shale, sandstone, and limestone	328	343
Macksburg 140-foot, or First Cow Run, sand	35	378
Shale and limestone	307	685
Macksburg 500-foot sand	17	702
Shale and sandstone	379	1,081
Maxville limestone (Big Lime)	35	1,116
Mississippian:		
Shale	5	1,121
Keener sand	55	1,176
Shale	15	1,191
Big Injun sand	115	1,306
Shale and sandstone	394	1,700
Berea sand	14	1,714

These oil sands vary greatly in persistence, texture, and thickness. Thus the Berea sand is nearly always found at the proper horizon, and its variation in thickness, excepting in a few places, is small. It is coarse-grained and samples shot from deep wells in southeastern Ohio look not unlike those obtained from quarries at Berea. The Big Injun and Keener sands are as a rule much coarser than the Berea and in fact at places are conglomeratic. Their thickness varies much, but they are always present. Along the line of outcrop these sands are known as the Black Hand conglomerate and Logan sandstone.

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[11] D. D. Condit: Personal letter, Dec. 11, 1916.

The Macksburg 500-foot sand does not appear to be persistent. It is at its best in the vicinity of Macksburg, where it was named, and lies 500 feet below the valley of Duck Creek. It is coarse-grained sand and in places a source of fine oil wells. The Macksburg 140-foot, or First Cow Run, sand is the best known of the shallow sands in Ohio. It is a prominent source of oil in Morgan, Noble, and Washington counties, but is not very persistent. Its best known field consists of a long, winding strip, nowhere a mile in cross-section, and in one place so narrow that a single row of wells suffices to get the oil. Elsewhere the pools are not so elongated. The sand where it produces oil is coarse-grained and drillers count on oil where this texture is found.

The wells of eastern Ohio have varied in depth from 12 feet to 2,200, and one well of only 38 feet is now being pumped. Shallow wells, and especially those in the Cow Run sand, are very long lived. Thus one well near Joy, Morgan County, and only 98 feet deep, has yielded oil continuously since 1872, and under artificial pressure now produces 3 barrels of oil per day. Wells in eastern Ohio have nearly all been small, and the records rarely show one having an initial production as high as 500 barrels per day, though as much as 2,400 have been reported. The depths, however, have not been great, and the long life of the wells and the high quality of the oil have made them a source of profit. The oil is of Pennsylvania grade, excepting a small number of pools, and usually varies from 42 to 50° Baumé in density. The most common color of the oil is dark green, but in places it is a bright red and elsewhere black.

In places such as the Cow Run, Newell Run, and Moore Junction oil pools, in Washington County, well marked anticlines exist, but in most oil fields in eastern Ohio no such relation is known. However, a careful investigation of the rock structure has not been made in many places where oil has been found. The contour maps of the oil sands which the Federal Survey has been issuing within the past 10 years show that the oil occurs in most places except in synclines, and in the writer's judgment the relation in these areas between oil and rock structure is somewhat obscure.

Petroleum is obtained from the Huron sandstone, which lies at the top of the Mississippian, in Gibson and Sullivan counties, in southwestern Indiana. While prospecting in this territory had been done in an irregular way for many years, the production did not assume commercial proportions until 1913. The wells are shallow, 600 to 900 feet, and hence inexpensive. In June, 1914, Sullivan County alone was yielding 3,500 barrels per day, and the production of the State for that year showed 40 per cent increase over that for the preceding year, the increase being due to this shallow sand. The relation of the petroleum to the rock structure has not yet been described.

Within the past few years Messrs. Smith and Dunn, of Marietta, Ohio, have devised and put into practice a method for increasing the production of old oil wells. Their aim is to restore to the oil rock the same condition of pressure that existed when the well was first drilled, and this is done by forcing air into the rock. Naturally the pressure applied varies with the texture of the rock, and in practice this ranges from 40 to 350 pounds to the square inch. The depth of wells in Ohio and West Virginia to which pressure has been applied varies from 43 to more than 2,000 feet, and the increase in oil has been as much as 800 per cent, based on a year's production, though the inventors do not claim more than 100 or 150 per cent increase on an average. Attempts to apply this system to the Trenton limestone field of Ohio and Indiana have thus far been unsuccessful.

Looking to the future of the petroleum supply, conditions are not at all encouraging in Ohio and Indiana. So extensively has drilling been done that no large areas remain untested. Every county has had at least one well drilled in it and most counties a half dozen or more. It is a reasonable conclusion, therefore, that large pools need not be expected, though small ones are probable. Both States reached the zenith of their production years ago, and the decline which then set in will continue, in all probability, with occasional interruptions, to the end.

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VOL. 28, PP. 677-684 SEPTEMBER 30, 1917

OIL FIELDS OF THE PACIFIC COAST[1]

BY ROBERT W. PACK

(Presented before the Society December 28, 1916)

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INTRODUCTION

In a space so limited as that which is available here one can not do more than sketch, in the shortest sort of an outline, the features characteristic of the oil fields along the Pacific coast of North America. The writer will, therefore, present here only a brief discussion of the broader geologic features that appear to be common to the California fields. Although these fields are among the more recently developed ones, and although the geology—stratigraphy and structure alike—of the region in which the fields lie is woefully complicated, still the larger geologic features that govern the occurrence of petroleum in these fields are pretty well known, probably better known than they are for many other fields in the United States. No attempt will be made to outline or to discuss the areas of prospective value or to estimate the quantity of petroleum available in this region.

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[1] This paper is one of a series composing a "Symposium on the Geology of Petroleum." See this volume, p. 156.

Manuscript received by the Secretary of the Society May 4, 1917.

Location of the Oil Fields

When one thinks of the petroleum resources of the Pacific coast of North America, it is the California fields that are the subject of attention; for, although oil is known to occur at other places in this general region, practically all the present production is obtained in California, and the most promising prospective territory is likewise located in that State.

Seeps of light gravity oil are known both in Alaska and along the northwest coast of Washington. Wells have been drilled at both places and a small quantity of oil produced in Alaska, but the results have not as yet proven the existence of any considerable quantity of oil. It is probable that, because of the complicated geology and the thick glacial and forest cover, the prospecting for oil in both places will be slow and expensive, and therefore that the development of these localities will await the exhaustion of the present better defined fields. As the information regarding these areas is so meager and in general so unreliable, this discussion will be confined to the California fields.

California for several years led all the States in the quantity of oil produced annually, and, although during the past two years it has been surpassed by Oklahoma, it still contributes more than 30 per cent of the total amount of oil produced annually in the United States. Were it not for the retardation in development caused by controversies as to title of lands within the productive fields, it is probable that the State would even now lead all others in the quantity of oil produced annually. Moreover, owing to the thickness of the productive sands, the annual decrease in production is relatively small as compared to the Oklahoma fields, and California will almost surely be in the first rank again before long.

All the producing fields in California lie in the coast ranges which border the Pacific Ocean and in the southern half of the State—that is, south of the Bay of San Francisco. Various seeps of oil of excellent quality, apparently superior to most of that obtained in the productive fields to the south, occur in the northern Coast Ranges—that is, northward from the bay as far as the Oregon line. This oil issues from Cretaceous shales and sandstones similar, both in age and in general lithologic character, to the beds yielding oil in the Rocky Mountain fields; but, unlike that region, the structure in the northern Coast Ranges does not appear to favor the accumulation of oil, for the beds are in the main steeply tilted and truncated along the flanks of the main mountain uplift. It thus appears that not only is the present supply of oil on the Pacific coast coming from a relatively small area in the southern Coast Ranges of California, but that the potential supply lies there, and that it is from this area that the oil which will be produced on the Pacific coast in future years will come.

The Coast Fields and the Valley Fields

In speaking of the oil fields of California it is quite usual to divide them according to geographic position into two groups—the coast fields and the valley fields. The coast fields are those that lie close along the Pacific Ocean or in relatively short valleys that drain directly into the ocean; the valley fields embrace those productive fields that lie about the southern end of the San Joaquin Valley, which is the southern half of the great trough that occupies the central part of California.

When viewed broadly, the general features of the various productive fields, both coast and valley fields, appear remarkably similar, for not only is the oil uniformly associated with a certain type of formation (although not necessarily with a formation of definite age), but the general structure is, with a few notable exceptions, of a like character. It is this knowledge that makes those of us who have worked in the California fields feel that we can with a reasonable degree of assurance say that the main productive areas within the State are at present outlined, and that the future production of the State will come chiefly from within the bounds of the fields that are now productive and from the areas immediately adjacent to those fields. Various pools isolated from those now yielding oil will no doubt be discovered from time to time in the southern Coast Ranges, but the total production from these pools will not be comparable with that which will be obtained in the fields now known. Such a statement as this may appear somewhat premature when one remembers that the geology of much of the State is only imperfectly known, yet the general features that it appears characterize every successful oil field in this region are fairly definite and may be recognized, even though the details of the geology are not known.

Origin of the Oil

The first, and probably the most striking, feature common to the fields is the presence in or immediately adjacent to them of thick masses of shale of organic origin. These shales are commonly known as diatomaceous shales, because of the abundance of the remains of diatoms that they contain. The oldest of these shales lies in the uppermost part of the

Cretaceous and the youngest in the upper Miocene. The sands yielding oil occur either intercalated with these shales, or immediately above or immediately below them, and in general the best sands are those that overlie the shales, especially if they rest unconformably upon the shale.

There has been a great deal of speculation regarding the origin of oil in different parts of the world, and even now there is by no means a general agreement as to just the manner in which it has come into being or from what materials it has been formed; probably no rule will fit all cases; but regarding the California fields the conclusion is unavoidable that the oil has originated in the diatomaceous shales, and, as these shales differ from the other shales in the general region only in the fact that they are composed largely of the remains of minute organisms, it likewise seems certain that it is from these organisms that the oil has been produced. Were this not the case, and were the oil formed in some other place, some explanation must be offered for the peculiar tendency of the oil to collect in the sandy beds in and about these organic shales, and yet to leave no trace in any of the sandy beds that occur in the thousands of feet of sedimentary rocks that overlie or underlie the shales, when to all appearances these sandy beds offer equally as attractive a reservoir for the collection of oil as do the beds in which the oil is now found.

Effect of geologic Structure on Accumulation of Oil

Second in importance only to the materials from which the oil is formed is the geologic structure, for the attitude of the beds determines the area beneath which oil has accumulated. The structure of the southern coast ranges of California is complicated, and the beds are both sharply flexed and considerably fractured, yet, despite that fact, oil has accumulated in many places and in many different types of structure. However, when one considers the more productive fields, one is immediately impressed with the fact that almost all these fields are located along anticlines—not necessarily close along the axes of these folds, but in areas where the folding has been distinctly upward and where the anticlinal fold may be said to be the dominant feature.

It is hardly pertinent here to enter into any discussion of the anticlinal theory or any of the other theories regarding the accumulation of oil, yet whatever have been the forces that caused the accumulation of oil in California, or however they have worked, it is apparent that they resulted in most cases in the collection of the oil in the anticlines rather than in any other place. The occurrence of oil in monoclines may be regarded as but special cases of the occurrence along anticlines, for these monoclines are essentially flanks of anticlines on which the Tertiary beds that contain the oil are truncated and outcrop. Oil contained in these truncated beds has, therefore, in the absence of an impervious capping stratum, free access to the surface, and theoretically may be forced out on the surface and lost by evaporation. Practically, however, no such free avenue of escape is available, for the California oils are easily oxidized to form a heavy viscous material which quite effectually clogs the pores of the bed (which acts as a reservoir) near its outcrop, and thus forms of it a tight container for the oil. The oxidation of the oil and its consequent tarrification is accomplished chiefly through the interaction of the oil and sulphate waters, which are the common surface waters in the California fields, and the subsequent addition of sulphur compounds to the oil.

Migration of the Oil

The migration of the oil that is now found in the productive fields has been extensive, and the accumulations of it have been drawn not only from the diatomaceous shale that lies within the geographic limits of the productive field, but also by lateral migration from shale lying far beyond those limits. In the valley fields, for example, the structures that contain the oil are located about the borders of the San Joaquin Valley—a great structural trough—in which it is evident there are great masses of diatomaceous shale buried beneath the younger sedimentary rocks. These shales in the center of the trough have, it is believed, contributed largely to the accumulations of oil now occurring about the edge of the valley.

It has frequently been urged that extensive lateral migration of heavy viscous oil, such as that found in many of the California fields, through fine-grained sedimentary rocks is inconceivable. But upon closer analysis it does not appear to be quite so impossible after all; for one must remember that the viscosity of these heavy oils varies tremendously with small changes of temperature, and that at a temperature of about 200° Fahrenheit they are hardly more viscous than the lightest Pennsylvania oils; also the petroleum now found in the California fields probably had a somewhat higher temperature when it moved into the position it now occupies than it has at present, and although this temperature may never have been so high as 200° Fahrenheit, still it was high enough to lessen greatly the viscosity. Finally, the petroleum has almost certainly been in contact more or less of the time with sulphate waters, and has, therefore, been liable to certain changes, chiefly the formation of sulphur compounds within the oil, which would tend both to increase the specific gravity and to make the resulting oil much more viscous.

Effect of Unconformities on Accumulation of Oil

Structural features of lesser importance than the anticlines, but still of very considerable importance in the consideration of the accumulation of oil, are the unconformities that separate the various formations, and particularly those that separate any one of the diatomaceous shales from the formation that rests upon it. The hydrocarbons, whether they be in the liquid or gaseous state in leaving the diatomaceous shales, tend naturally to follow the bedding planes, or the sandy beds intercalated with the shale, for it is along these lines that the resistance to movement is least. If the shales are truncated along the plane of unconformity, these hydrocarbons tend gradually to accumulate in the usually sandy bed that forms the lowest member of the formation resting unconformably upon the shale, and it is the beds occupying this position that are the chief oil sands in the productive fields.

Geologic Features determining Presence of Oil

These, then, are the more important general geologic features of the California oil fields, the features that seem to determine whether or not oil occurs at all in the region, and, if it exists there, in what parts of the region it has probably accumulated in considerable amounts: (1) the deposits of diatomaceous shale in which the oil had its source; (2) the anticlines or equivalent structures furnishing the traps for holding the oil, and (3) the unconformable relationship existing between the shale and the overlying beds, affording easy passage for the oil through the rocks to an entrance into these traps.

The Province of the Geologist

Although it seems certain that the position of the main oil-bearing lands in California is known, and that the pools which will be discovered in the future will probably not be comparable with those now known, still the work of the geologist is by no means ended there; rather has it only just begun. Too frequently the work of the petroleum geologist is thought to consist only of the estimation of untested lands, of the search for new fields to conquer, and of new pools for the operator to drain. A great deal has been said about the aid a geologist may be to the prospector, particularly of the service he may render in the prevention of the waste of energy and of money in foolish drilling; but much too little thought is given to the help that he may render the operator in the efficient draining of the pool.

In the very nature of things, the first well drilled into a new pool must go more or less blindly, but with the information derived from it and from each succeeding well, drilling should become less and less a matter of faith and more and more an exact science. The determination of the position of the top of the producing zone, important as such a determination may be, is only the least part of the work, for to be of real value the study of these data should show the position of each producing oil sand within the zone, and, which is frequently of even greater importance, the position of each water sand. Then, as the true nature of the natural conditions—that is, the conditions existing before drilling commenced—becomes known, it becomes possible to understand the nature of the conditions produced when the movement of the fluids is interfered with by the wells that are drilled.

But in order that this may result—in order that each new well in a field may not continue to be a special and isolated venture—it is necessary that a systematic record be kept of the data furnished by the wells, and that the geologic significance of these data be interpreted by some one competent to make such interpretations.

The importance of the data made available through development work has for years been thoroughly appreciated by those engaged in a study of the geology of solid minerals, and a large part of a report on the geology of any mining camp consists of the interpretation of these data. It seems truly remarkable that so little attention should in the past have been given to the like interpretation of data made available by the wells in an oil field. Deposits of solid minerals are not migratory, and an unchanging quantity of mineral is allotted to each tract of land. If it is profitable, in developing deposits of this type, to make careful studies of all available data, how much more necessary should it be to make similar studies in exploiting deposits of such vagrant minerals as oil and gas.

Some of the larger companies in California appreciate the fact that the scientific study of the geology of a field will be profitable to them, and a few are keeping up a systematic investigation of the part of the field in which they operate. But the investigation of no company completely covers any of the larger fields, and the many small operators must of necessity still work more or less blindly. Such investigations properly should be undertaken by some branch of the Government, and the assistance already given by both the State and the Federal governments have been of great service; but there is room for more work than has as yet been done.

Recent estimates of the amount of oil remaining available in the fields now producing in California have shown that, large as the total quantity is, it probably will not be sufficient to supply the needs of the next generation. As these fields appear to contain most of the available oil on the Pacific coast, it behooves us to see that the extraction of this oil is thorough and efficient.

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THE MID-CONTINENT OIL FIELDS[1]

BY JAMES H. GARDNER

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[1] This paper is one of a series composing a "Symposium on the Geology of Petroleum." See this volume, p. 156.

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Introduction

The Mid-Continent oil fields lie in Kansas, Oklahoma, northern Texas, and northern Louisiana, including also the gas-producing territory of western Arkansas.

The writer has included herewith a map of each of the States under discussion, showing geological boundaries and the locations of the various oil and gas fields. Structure contour sketches are given of typical areas in several districts in order to illustrate the effects of rock folding on oil and gas accumulation.

Output of the several Fields

For brief comparison, it may not be amiss to call attention to the fact that in 1915 the Mid-Continent fields produced 123,295,867 barrels of petroleum, which lacked only about 17,000,000 barrels of having been half of all the oil produced in the entire United States. Oklahoma led all other States, having exceeded California by over 11,000,000 barrels.

For the purpose of comparing the respective districts of the Mid-Continent region, as they are now producing, the estimated daily production at the end of the second week of this month (December, 1916) follows: Kansas, 76,250 barrels; Oklahoma, outside of Cushing, Healdton, and Shamrock, 120,000 barrels; Cushing and Shamrock, 89,000 barrels; Healdton, 64,000 barrels; Electra, Texas, 25,000 barrels; Corsicana (light grade) and Thrall, Texas, 1,500 barrels; Caddo, of Louisiana and Texas, 25,000 barrels. Total for all the fields was 401,250 barrels. For the same period the Gulf Coast fields, including the heavy petroleum from Corsicana, Texas, produced about 52,500 barrels.

Relationship of the Areas

The oil and gas fields of Kansas and those of Oklahoma are closely related and might appropriately be discussed under the same heading. For instance, the accumulations are found chiefly in strata of the Pennsylvanian series, which lie in connected outcrop across the eastern portion of both States; the numerous producing areas, or so-called "pools," fall into one general group, and each owes its presence to depositional and structural features of the same general type and origin. However, the isolated fields of northern Texas and southern Oklahoma, as well as those of northern Louisiana, fall into different geological and physical provinces, and in a paper of greater scope and more detail should be described separately. In order to systematize the discussion along definite lines, the writer shall briefly consider the subject by States.

KANSAS

LOCATION OF THE FIELDS

The northernmost of the Mid-Continent fields are in the southeastern portion of Kansas and are coextensive with a broad zone of disconnected fields in Oklahoma. The oil-producing formations lie in the Pennsylvanian series and accumulation has taken place mainly on local structures along the west flank of the Ozark Arch (see figure 1).

STRATIGRAPHY

The following is a general stratigraphic section of rocks in the oil-bearing region of Kansas, showing the horizons of the principal oil-producing sands.

The following general stratigraphic section in the oil and gas region of Kansas is given in descending order:

	Feet
Permian series.	
1. Red and gray sandstone strata with beds of red and vari-colored shale. Includes salt and gypsum in upper portion. Much like Upper Permian in Oklahoma	1,000–1,500
2. Wellington shale	75–150
3. Marion limestone	100–200
4. Winfield formation; limestone and shale	20–30
5. Doyle shale	50–70
6. Fort Riley limestone, outcrops at Augusta	40–50
7. Florence flint	15–25
8. Matfield shale	60–70
9. Wreford limestone	35–55
(Base of Permian according to Prosser.)	
10. Neosho formation and Florence shale	140–150
11. Cottonwood limestone	5–10
12. Eskridge shale	30–40
13. Neva limestone	5–15
14. Elmdale formation; shale and lime	120–140
(Base of Permian according to Beede.)	
Pennsylvanian series.	
1. Americus limestone	6–10
2. Admire shale, probably includes oil sand at a depth of about 650 feet at Eldorado	275–325
3. Emporia limestone	5–10
4. Willard shale	60–190
5. Burlingame limestone	6–12
6. Scranton shale	160–180

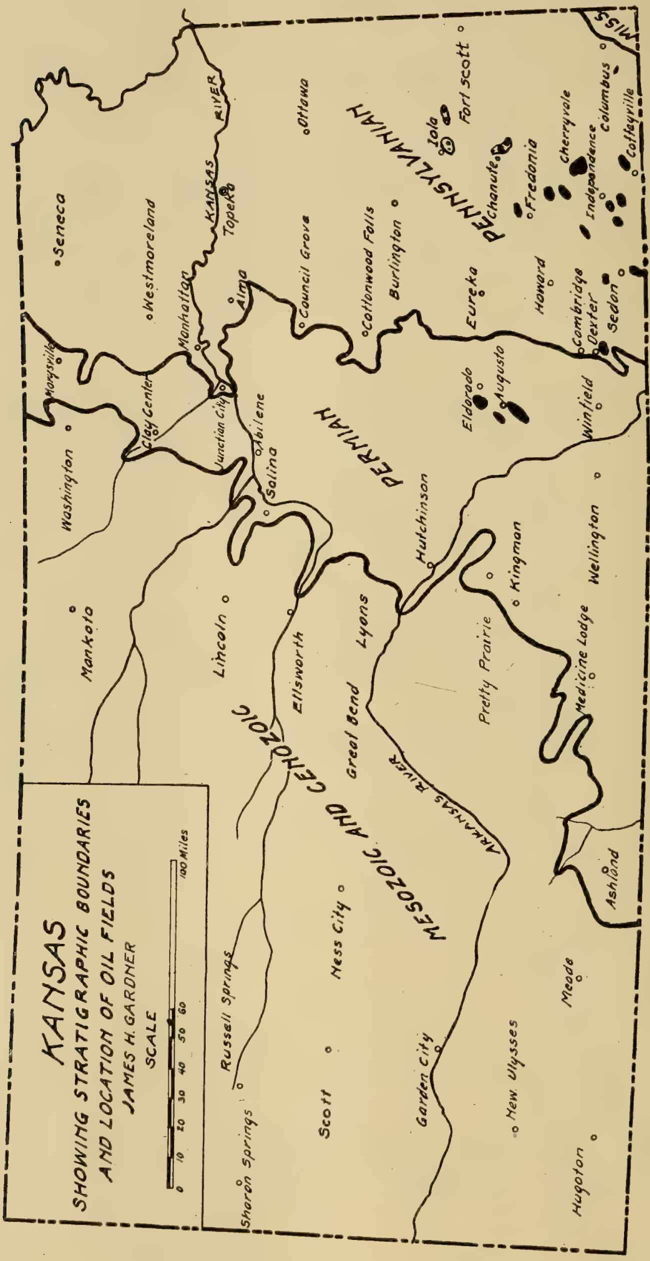
KANSAS
SHOWING STRATIGRAPHIC BOUNDARIES
AND LOCATION OF OIL FIELDS
JAMES H. GARDNER
SCALE
0 10 20 30 40 50 60 100 Miles
PENNSYLVANIAN
PERMIAN
MESOZOIC AND CENOZOIC
KANSAS RIVER
ARKANSAS RIVER
MISS.
Seneca
Westmoreland
Topeka
Ottawa
Fort Scott
Iola
Chanute
Fredonia
Cherryvale
Independence
Columbus
Coffeyville
Council Grove
Cottonwood Falls
Burlington
Eureka
Howard
Cambridge
Dexter
Sedan
Alma
Manhattan
Marysville
Clay Center
Junction City
Abilene
Salina
Eldorado
Augusta
Winfield
Washington
Hutchinson
Kingman
Wellington
Mankato
Lincoln
Ellsworth
Lyons
Pretty Prairie
Medicine Lodge
Great Bend
Russell Springs
Ness City
Ashland
Meade
Scott
Garden City
New Ulysses
Sharon Springs
Hugoton

FIGURE 1.—Geologic Sketch Map of Kansas, showing Locations of Oil and Gas Fields

	Feet
Pennsylvania series.	
7. Howard limestone	2– 7
8. Severy shale	40– 60
9. Topeka limestone	20– 25
10. Calhoun shale	0– 50
11. Deer Creek limestone	20– 30
12. Tucumseh shale	40– 70
13. Lecompton limestone	15– 30
14. Kanawa shale	50– 100
15. Oread limestone	10– 25
16. Lawrence shale; includes Chautauqua sandstone member, which is the best exposed and most persistent bed of sandstone in this portion of the section. Probably correlates with the surface bed at Toronto. Occurs at 1,550 feet in wells at Augusta and Eldorado	200– 300
17. Kickapoo limestone	5– 15
18. Le Roy shale	60– 100
19. Stanton limestone	20– 40
20. Vilas shale	5– 125
21. Allen limestone	6– 75
22. Lane shale	30– 150
23. Iola limestone	2– 44
24. Chanute shale	20– 30
25. Drum limestone	3– 70
26. Cherryvale shale. About the horizon of the oil sand occurring at 2,450 feet at Augusta and Eldorado	40– 50
27. Dennis limestone, Galesburg shale, and Mound Valley limestone	80– 100
28. Ladore shale	20– 25
29. Bethany Falls limestone	15– 25
30. Pleasanton shale	20– 60
31. Coffeeville limestone	40– 60
32. Walnut shale	20– 140
33. Altamont limestone	25– 60
34. Bandera shale	50– 110
35. Pawnee limestone. Horizon of Peru oil sand	10– 65
36. Labette shale	25– 30
37. Fort Scott (Oswego) limestone	20– 70
38. Cherokee shale. Includes main oil sands of Kansas outside of Augusta and Eldorado regions. Contains Bartlesville and Burgess sands	375– 400
Mississippian series.	
Limestone, calcareous shale and chert shown in Neosho well. Boone formation	320
Probably older than Mississippian.	
1. Dolomitic limestone, sandstone, and chert in Neosho well.	77
3. Conglomerate and shale in Neosho well	23
4. Sandstone, conglomeratic with pebbles up to three-quarters inch in diameter; shown in Neosho well	1,823

In the Pennsylvanian series of Kansas limestone constitutes a very large percentage of the whole. Southward in Oklahoma limestone is of rapidly diminishing importance in the Pennsylvanian, the same being chiefly sandstone and shale. This is a very noteworthy change in the nature of the sedimentation, when one considers the fact that Kansas lies directly north of Oklahoma along the strike and continuous outcrop of the series. It bears testimony that deeper waters prevailed to the north and northwest in Pennsylvanian time. While some of the sandstones of Oklahoma are of deep marine origin, as shown by both paleontologic and lithologic evidence, a large percentage of them were unquestionably deposited in brackish or shallow water; they show ripple-marks on bedding planes and contain large casts of fossil trees; moreover, they alternate with beds of shale carrying plant remains and percentages of carbon varying from a trace to sufficient amounts to color the beds black. Such sediments are common in the strata through the oil belt of Kansas, and well logs show that near the Oklahoma line the formations are similar to those farther south. Northward in Kansas, however, the beds of shale contain less carbonaceous matter and more lime than they do in Oklahoma.

That an ocean lay to the west as well as to the north of Oklahoma and Kansas in Pennsylvanian time is further indicated by the fact that the sediments of the same age in southern Colorado and northern New Mexico are almost entirely of marine origin. Some years ago the writer made a stratigraphic section across the massive limestone beds near the town of Glorietta, New Mexico. Fossil Brachiopoda from that thick section of limestone were identified by Dr. George H. Girty, who pronounced them of Pennsylvanian age, and hence these limestones occupy the same general time interval as the sandstone and shale beds of the oil-bearing region in southeastern Kansas, eastern Oklahoma, and northern Texas. Other changes in the physiographic conditions during Pennsylvanian deposition are shown in the stratigraphy of Oklahoma and Texas.

In the Mid-Continent fields there is strong evidence that petroleum originated in largest quantities in rocks that were deposited in a position intermediate between near-shore sediments and those of the deep sea.

STRUCTURE

The topographic relief of the Ozark region east of Kansas is moderate, but the influence of the rise of igneous rocks in that territory was extensive. In fact, it now appears that effects of this disturbance can be observed in the sedimentary strata for the full length of Kansas east and west. All rocks from the Mississippian to the Cretaceous, inclusive, show the results of compression, as if lateral pressures to the westward accompanying the Ozark movement were opposed by pressures in the opposite direction from the Rocky Mountains. The strata of the intervening territory were here and there folded into anticlines, domes, terraces, and monoclines with numerous sharp irregular waves or "noses" along the strike. These subordinate structures are the ones that control the position of the oil and gas fields in southern Kansas and eastern Oklahoma.

The local folding in Kansas was not regularly formed like the long anticlines and synclines west of the Allegheny Mountains in Pennsylvania and West Virginia, nor of those that border the Choctaw fault to the southeast of the oil fields of Oklahoma. It is the rule in Kansas that oil and gas occur on low folds separated from one another and showing a tendency along the west limit of the fields to line up in a chain of related bulges trending with the strike. Farther east in the State no definite relationships can be worked out between neighboring structures, for they occur without system and are distinct in type and form. Favorable conditions for testing with the drill are often discovered in districts where they are least expected.

The strata of the Mississippian, Pennsylvanian, and Permian series dip normally westward across Kansas at the average rate of about 30 feet per mile. Across the oil fields the strike line is generally east of north and west of south. Locally the strata are horizontal or dip to the eastward, reversing the normal dip. The total amount of the reverse dip in feet constitutes the height of the structures, and varies from zero on the terraces or noses to as much as 150 feet or more in the oil fields at Augusta and Eldorado, or in the domes at Dexter and Elmdale, for examples (see figure 2).

OCCURRENCE OF GRANITE IN DOMES

In connection with the structure of the Kansas fields, attention is called to the occurrence of granite at reasonably shallow depths on some of the local domes in that State. At Elmdale, Onaga, Wabaunsee, and Zeandale granite is encountered at stratigraphic horizons as high as 1,000 feet above the base of the Pennsylvanian series. The fact that there is no evidence of metamorphic action in the beds of shale and sandstone immediately overlying these crystalline masses indicate that they are old knobs which stood submerged in the Pennsylvanian sea. Deposition filled around them until they were ultimately covered, and at these points subsequent compression developed lines of weakness, with consequent folding of the strata above the knobs. The dome at Elmdale shows a reverse dip of nearly 300 feet at angles as steep as 5 degrees. The depth from the present surface to the top of the granite varies from 950 feet on the structure at Zeandale to 2,500 feet on the dome near Cottonwood Falls or Elmdale.

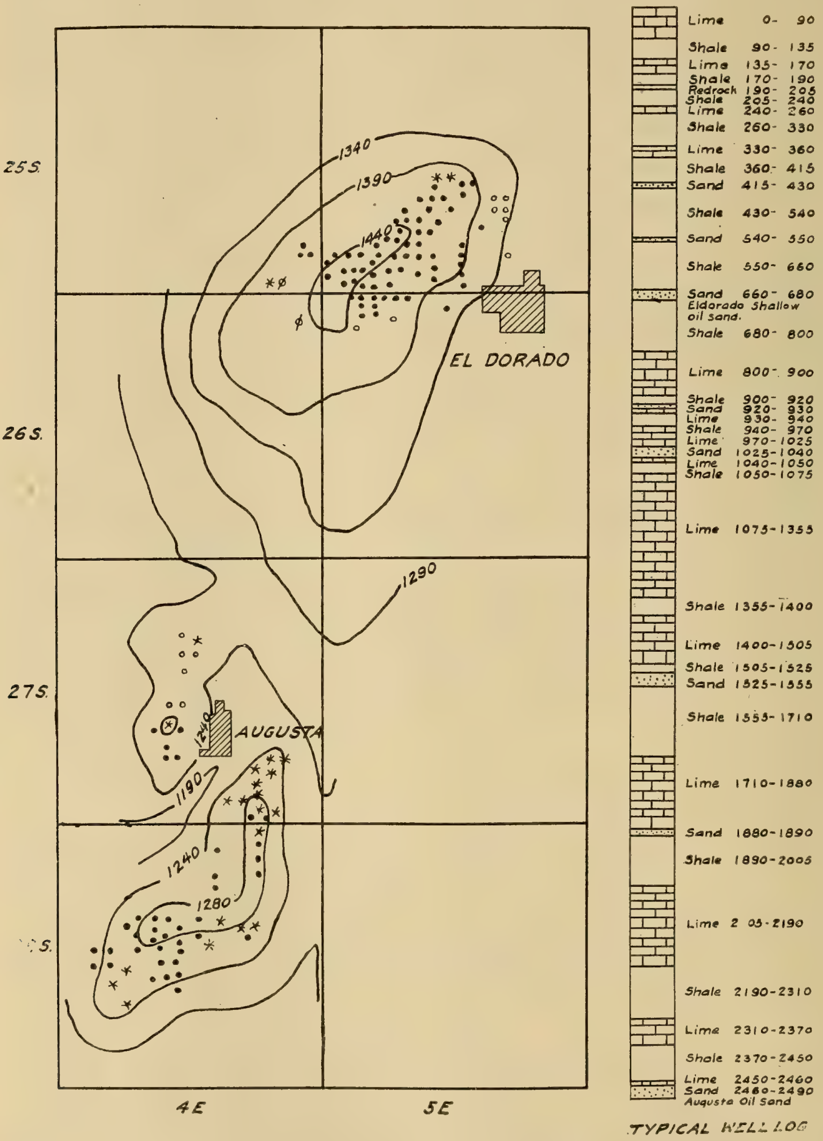
25S.
26S.
27S.
S.
4E
5E
1340
1390
1440
1290
1240
1190
1240
1280
EL DORADO
AUGUSTA
Lime 0- 90
Shale 90- 135
Lime 135- 170
Shale 170- 190
Redrock 190- 205
Shale 205- 240
Lime 240- 260
Shale 260- 330
Lime 330- 360
Shale 360- 415
Sand 415- 430
Shale 430- 540
Sand 540- 550
Shale 550- 660
Sand 660- 680
Eldorado Shallow oil sand.
Shale 680- 800
Lime 800- 900
Shale 900- 920
Sand 920- 930
Lime 930- 940
Shale 940- 970
Lime 970-1025
Sand 1025-1040
Lime 1040-1050
Shale 1050-1075
Lime 1075-1355
Shale 1355-1400
Lime 1400-1505
Shale 1505-1525
Sand 1525-1555
Shale 1555-1710
Lime 1710-1880
Sand 1880-1890
Shale 1890-2005
Lime 2 05-2190
Shale 2190-2310
Lime 2310-2370
Shale 2370-2450
Lime 2450-2460
Sand 2460-2490
Augusta Oil Sand
TYPICAL WELL LOG

FIGURE 2.—*Structure Contour Map of Augusta and Eldorado Oil Fields, Kansas, based on Outcrop of Fort Riley Limestone*

From maps by Dorsey Hager, Mowry Bates, and Lucian Walker

OKLAHOMA

PRODUCTIVITY OF THE FIELD

Recently discovered fields have given fame to Oklahoma the world over for its enormous production of high-grade petroleum.

STRATIGRAPHY

The Pennsylvanian series furnishes the main supply of oil-producing sandstones in Oklahoma, as shown in the following general stratigraphic section of rocks (see also figure 3).

GENERAL STRATIGRAPHIC SECTION IN MAIN OIL AND GAS DISTRICT OF NORTHERN OKLAHOMA

	Feet
Cretaceous series (see section further on).	
Permian series.	
1. Red and gray sandstone, clay-iron conglomerate, red and vari-colored shale; thin beds of concretionary limestone near base; beds of gypsum and salt in upper portion. Quartermaster, Greer, Woodward, Blaine, and upper portions of Enid formations; latter includes the Marion limestone of Kansas which outcrops around Blackwell, Oklahoma	1,200–2,000
2. Fort Riley limestone and other beds of thin limestone, sandstone, and shale down to the Neva limestone, inclusive. Contains near base the shallow gas sands at Blackwell, Billings, and Garber	500– 600
3. Elmdale formation; included in Permian of Kansas by Beede, but of uncertain occurrence in Oklahoma.	
Pennsylvanian series.	
Ralston group:	
Includes limestone and shale beds of Kansas section from Americus limestone down to Lecompton limestone, inclusive. In Oklahoma, however, consists of red and gray sandstone, red shale, and beds of thin limestone. Contains the Garber oil sand.	
1. Upper division down to Pawhuska limestone, inclusive	650
2. Lower division down to top Elgin sandstone	140
Sapulpa group:	
1. Elgin sandstone. Probable horizon of shallow oil sand in the Newkirk field and at Ponca City	20– 150
2. Oread limestone	0– 20
3. Buxton sandstone and shale. Horizon of main oil sand at Ponca City and gas sand at Myers	700–1,000
4. Avant limestone	0– 10
5. Ramona formation. Sandstone, shale, and thin limestone beds. Includes Lost City limestone and the Musselman oil sands of the Cushing-Cleveland areas	300– 400

	Feet
6. Dewey limestone	15– 25
7. Skiatook formation; sandstone, shale, and thin limestone beds. Includes Hogshooter limestone and Layton oil sand	350– 400
8. Lenapah limestone	10– 20
Tulsa group:	
1. Nowata shale; includes the Wayside oil sand and its correlations	75– 150
2. Oolagah limestone or "Big Lime" of the drillers	20– 50
3. Labette shale (local coal bed, Dawson coal)	75– 100
4. Claremore formation. Sandstone, shale, and beds of thin limestone. Contains at the base the Fort Scott or Oswego limestone. Includes the Cleveland and Peru oil sands	275– 350
Muskogee group:	
Beds of shale, sandstone, and thin limestone correlating with the Cherokee shale (Boggy and Winslow formations at Muskogee). Includes the main oil sands of Oklahoma; the Red Fork, Bartlesville, (Glenn), Tucker, Taneha, Booch, Morris, and Muskogee sands, the latter lying at the unconformable base of the Pennsylvanian series	450–1,500
(Unconformity.)	
Mississippian series.	
1. Morrow limestone	100– 200
(Unconformity.)	
2. Pitkin limestone	40– 60
3. Fayetteville formation. Sandstone, shale, and limestone. Contains the Mounds oil sand and a deep sand near Sapulpa	20– 200
(Unconformity.)	
4. Boone formation. Massive white limestone and massive beds of chert	200– 400
Devonian system.	
1. Chattanooga formation. Black fissile shale	30– 50
2. Sylamore sandstone; clear quartz sandstone	0– 25
(Unconformity.)	
Ordovician system.	
1. Tyner formation; thin sandstone and limestone in shale.	60– 100
2. Burgen (St. Peter) sandstone; massive quartz sandstone.	5– 100
Cambrian system.	
Massive limestone beds shown in Harrington well at Joplin, Missouri	1,165

The lower portion of the Pennsylvanian series and older rocks thicken in the southeast portion of Oklahoma at the rate of appropriately 100 feet per mile from Muskogee southward. The following is the general section for the McAlester-Coalgate-Atoka region.

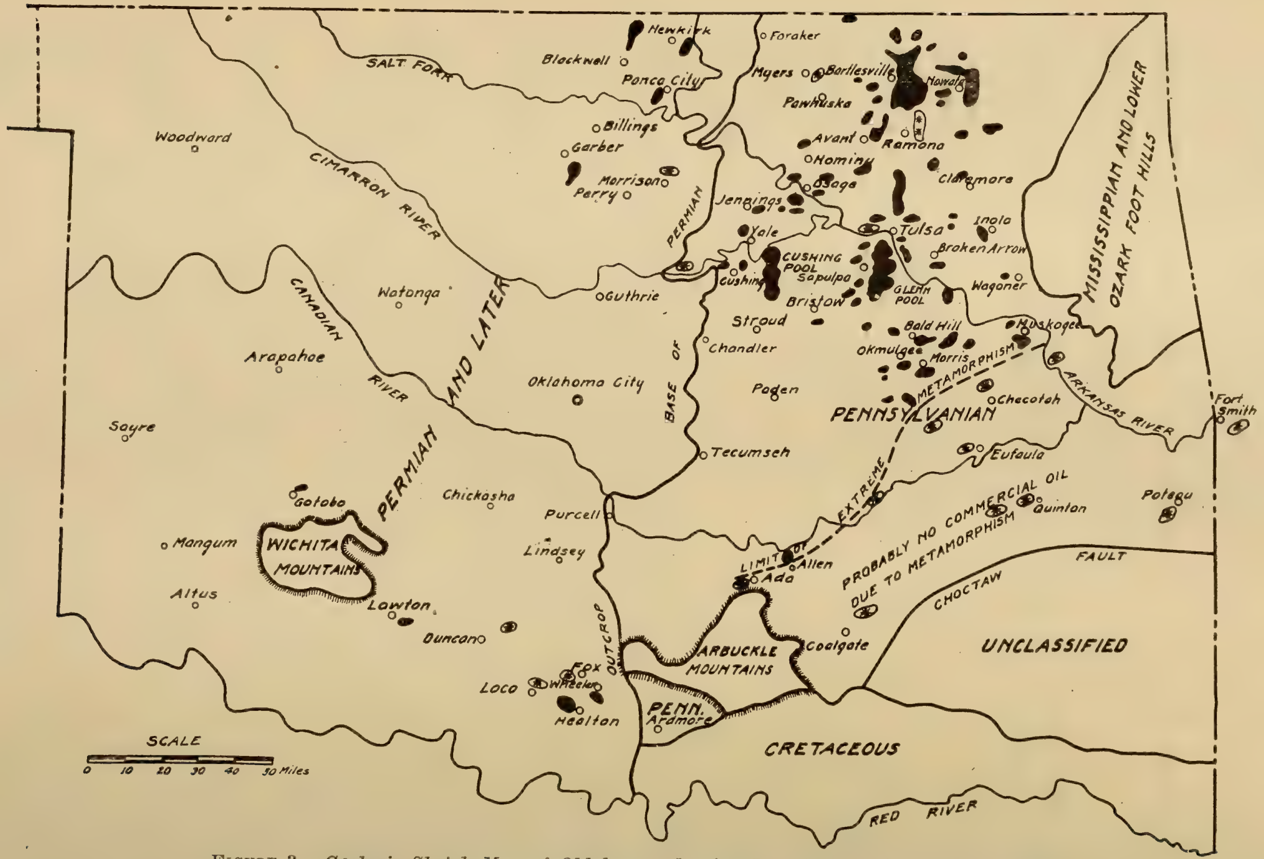
Woodward
SALT FORK
CIMARRON RIVER
Blackwell
Newkirk
Ponca City
Billings
Garber
Morrison
Perry
Foraker
Myers
Bartlesville
Nowata
Pawhuska
Avant
Ramona
Hominy
Osage
Claremore
Jennings
PERMIAN
Yale
Tulsa
Inola
Broken Arrow
CUSHING POOL
Cushing
Sapulpa
GLENN POOL
Wagoner
Bristow
Guthrie
Watonga
CANADIAN RIVER
AND LATER
Arapahoe
Stroud
Chandler
Bald Hill
Muskogee
Okmulgee
Morris
METAMORPHISM
Oklahoma City
BASE OF
Paden
Chechotah
PENNSYLVANIAN
ARKANSAS RIVER
Fort Smith
Sayre
PERMIAN
Tecumseh
Eufaula
EXTREME
PROBABLY NO COMMERCIAL OIL DUE TO METAMORPHISM
Quinton
Poteau
Gotebo
Chickasha
Purcell
WICHITA MOUNTAINS
Mangum
Lindsey
LIMIT OF
Allen
Ada
FAULT
CHOCTAW
Altus
Lawton
Duncan
OUTCROP
ARBUCKLE MOUNTAINS
Coalgate
UNCLASSIFIED
Fox
Wheeler
Loco
Healton
PENN.
Ardmore
SCALE
0 10 20 30 40 50 Miles
CRETACEOUS
RED RIVER
MISSISSIPPIAN AND LOWER OZARK FOOT HILLS

FIGURE 3.—*Geologic Sketch Map of Oklahoma, showing Location of Oil and Gas Fields*

GENERAL STRATIGRAPHIC SECTION IN SOUTHEASTERN OKLAHOMA, NORTH OF ARBUCKLE MOUNTAINS

The following general stratigraphic section in southeastern Oklahoma is given in descending order:

	Feet
Lower portion of Pennsylvanian.	
1. Seminole conglomerate and Holdenville shale	250– 300
2. Wewoka formation. Sandstone and shale with beds of thin limestone	500– 800
3. Wetumka shale	120
4. Calvin sandstone. Approximate horizon of Oswego limestone in north area	140– 240
5. Senora sandstone	140– 485
6. Stuart shale	90– 280
7. Thurman sandstone	80– 260
8. Boggy shale with beds of thin sandstone; limestone and thin irregular coal at base	2,000–2,600
9. Savanna sandstone; massive sandstone strata with beds of shale (horizon of Bartlesville sand)	1,000
10. McAlester shale. Includes strata of sandstone. Coal beds of the McAlester-Coalgate region (Oklahoma coal field)	1,800–2,000
11. Hartshorne sandstone	150
12. Atoka formation. Massive beds of sandstone with alternating beds of shale	3,100
13. Wapanucka limestone	100
Mississippian series.	
1. Caney shale	1,500
Devonian system.	
1. Woodford chert	600
Ordovician and Silurian systems.	
Sandstone, shale, and limestone	5,000–7,000
Cambrian system.	
Reagan sandstone	100
(Unconformity.)	
Pre-Cambrian granites.	

South of the Arbuckle Mountains both the Permian and Cretaceous show strong angular and erosional unconformities with lower rocks, so that a considerable portion of the original beds are missing.

The following section applies to that region:

GENERAL STRATIGRAPHIC SECTION SOUTH OF THE ARBUCKLE MOUNTAINS IN OKLAHOMA

	Feet
Lower Cretaceous system (Comanche series).	
1. Silo sandstone	200
2. Pennington limestone	10– 15

	Feet
Lower Cretaceous system (Comanche series).	
3. Bokchito formation	140
4. Caddo limestone	60
5. Kiamichi formation	150
6. Goodland limestone	25
7. Trinity sand, which includes the oil sand in the Madill field and gas sand at Woodville	200– 400
18. (Unconformity.)	
Permian series.	
Red sandstone, vari-colored shale, and beds of clay-iron conglomerate with thin lenses of limestone	400–1,500
(Unconformity.)	
Pennsylvanian series.	
1. Franks conglomerate. Limestone (Wapanucka) at top. Beds of chert, gravel, boulders, and sandstone; formation of local extent near mountains	500
2. (Unconformity.)	
Glenn formation; blue shale with lenticular beds of sandstone. Probable horizon of the main oil sand in the Healdton field (see under Ordovician system)	1,000–3,000
(Unconformity.)	
Mississippian series.	
1. Caney shale. Top is blue shale with sandy lentils and lower portion is black fissile shale with concretions of dark-blue fossiliferous limestone	1,500
2. Sycamore limestone	0– 160
Devonian system.	
Woodford chert	600
Silurian system.	
1. Hunton limestone	0– 200
2. Sylvan shale. Blue clay shale	50– 300
Ordovician system.	
1. Viola limestone; white and bluish	750
2. Simpson formation; siliceous sandstone, bituminous sandstone, fossiliferous limestone, calcareous sandstone and shale (possibly contains deep oil sand at Healdton)	1,600
Cambro-Ordovician systems.	
Arbuckle limestone; massive and thin bedded, white and light blue limestone with cherty concretions	4,000–6,000
Cambrian system.	
Reagan sandstone; coarse dark brown sandstone with calcareous sandstone and shale at top	50– 150
Precambrian system.	
Tishomingo granite.	

The Pennsylvanian series in Oklahoma is made up of beds of sandstone alternating with strata of gray, blue, and dark shale, with thin beds of limestone at widely separated intervals. Coal in commercial quantities occurs in a very limited portion of the basal section and in a district southeast of the oil fields. The McAlester-Coalgate region, which contains the coal beds, extends over a small percentage of the Pennsylvanian outcrop. Wells drilled for oil and gas in the oil-bearing region have penetrated all portions of the Pennsylvanian series from the uppermost member down to the Mississippian limestone, but seldom do the logs show any coal whatever. In the vicinity of Tulsa and northward the Dawson coal bed is worked in a small way by stripping and shallow drifts; it is a bed of slight thickness and limited extent, although interesting, in that it occurs abnormally high in the series. There is also a local occurrence of coal near Foraker, in Osage County, which lies at a still higher stratigraphic level.

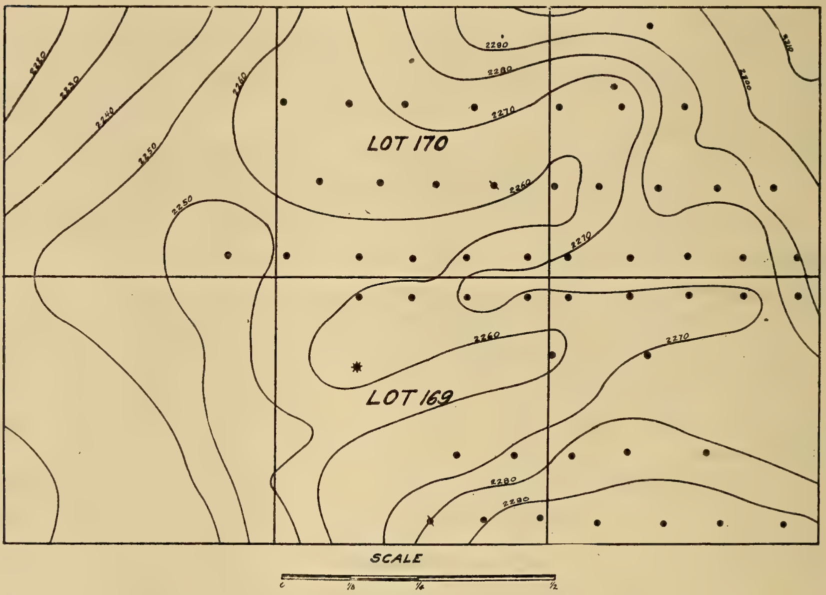

FIGURE 4.—*Structure Contour Map in eastern Osage County, Oklahoma, showing crumpled Nature of the Folding, based on Well Logs to Bartlesville Sand*

From map by F. Julius Fohs

Certain beds of sandstone in the Pennsylvanian section, or sandy, fractured limestone, such as the Wheeler, constitute the so-called "oil sands." Sandstones in the Mississippian series and the Cretaceous system have furnished oil and gas to a limited extent, but less than one per cent of the oil produced in the State comes from these strata. The Permian series, which contains a notable amount of gas on the Blackwell anticline at shallow depths, has recently been shown to contain gas on a dome at Garber and at shallow depths on an anticlinal structure at Billings. However, the nature of the Permian over a great part of its area in Oklahoma is adverse to its proving an oil-bearing series of much note. As a rule, its strata are subaerial in origin and were thoroughly oxidized and leached of oil-bearing materials at the time of deposition. The Permian in Oklahoma is ordinarily referred to as the "Red Beds," owing to the prevailing color of the sandstone and shale beds that compose it. But northward into Kansas the lower portion of the series changes its nature and is composed of beds of blue, black, and gray shale, thin beds of limestone and gray sandstone. The fact that gas is found in Permian sands on certain structures in Oklahoma and Kansas suggests the possibility that these sands may carry oil locally in some districts of this general region.

Throughout much of the Permian area the upper members of the Pennsylvanian series lie just beneath the base thereof and offer splendid chances of furnishing new oil fields. In fact, the well of the Sinclair Oil and Gas Company on the Garber dome has recently encountered a sand in the top of the Pennsylvanian at 1,100 feet, which for some weeks (December, 1916) has been flowing at the rate of 60 to 100 barrels per day. This is an entirely new oil-producing horizon in Oklahoma, and is certainly a very important discovery in looking forward to the future oil possibilities of the territory farther west in that State and Kansas.

Heretofore it has been the custom for operators in the Pennsylvanian area of Oklahoma to stop drilling at the top of the Mississippian limestone; but the time is at hand when test wells on good structure should be drilled down into and through the Mississippian for possible oil sands at deeper levels (see the general sections presented herewith). Very few test wells, even in the shallow area, have been drilled to a sufficient depth to encounter the Sylamore sandstone of the Devonian or the Burgen, sandstone of the Ordovician systems. The writer has observed residue oil in considerable quantities in the Sylamore sandstone in Cherokee County, Oklahoma, where it outcrops east of the oil fields.

STRUCTURE

Structural features that accompany the concentration of oil and gas in Oklahoma are of two types: the regional and the local. The oil fields lie within certain general areas, due to the position of those areas with respect to surrounding mountains, but actual concentration is confined to irregular folding of the strata in local districts. Approaching the Ouachita Mountains from the north the Pennsylvanian series passes into an area of steeply folded anticlines and synclines running northeastward and southwestward parallel to the Choctaw fault. This region has suffered extreme compression of the strata, so that the coal beds run as high as 70 per cent carbon on a moisture-ash-free basis, due to the metamorphic effects of this great thrust. David White has called attention to the fact that such areas seldom supply commercial oil fields, but frequently furnish gas fields. This portion of Oklahoma and that extending into Arkansas around Fort Smith and Kibler illustrate this fact in a splendid manner. The gas fields in this district do not carry oil with them; in fact the gas is extremely dry. The limit of the region thus affected lies far within the Pennsylvanian area and is marked by a fairly definite line which the writer has drawn on the accompanying map of Oklahoma.

The local structures that contain the oil and gas fields of Oklahoma are related to the Ozark uplift, the Ouachita and Arbuckle Mountains uplift, the Choctaw fault, and the Wichita Mountains uplift. The oil-bearing folds fall into two classifications; one class is that of the distinct isolated structure standing separately and definitely disconnected from all others. These have well marked and consistent boundaries, such as, for instance, the elongated dome or short anticline that produced the Cushing field (see figure 5). The other class is the producing zone, or a more or less disconnected, irregular area of crumpling that covers so much territory that the term "oil pool" as used by the operator is not applicable to it; as a concrete illustration of this type the production in eastern Osage County and about Bartlesville may be cited (see figure 4).

In Oklahoma the nature of local structure in its relation to the presence of salt water determines the respective class into which any particular oil field falls. In some districts, for instance, the oil-bearing sandstones, or "oil sands," contain an abundance of salt water under strong hydrostatic head, in which case the oil and gas have been sharply segregated from the water-bearing areas and pushed under the portions of the structure where the sands lie highest above a given datum plane. As a rule in such districts both petroleum and gas lie relatively high on structure, and the sands about them are strongly saturated with brine. In that portion of Oklahoma and Kansas west of the Ninety-sixth Meridian, which runs through Tulsa, Oklahoma, and a short distance west of Independence, Kansas, most of the oil and gas fields lie on what are usually referred to by geologists as "closed structures"—that is to say, on domes or anticlinal bulges. As a matter of fact, the western extension of this region lies down the dip of the strata, where the main oil sands are at depths below 1,800 feet, and the hydrostatic head of the salt-water saturation is strong. It is an interesting fact that the closed pressure on the oil and gas wells in this portion of the Mid-Continent region closely approximates figures for the hydrostatic head of a column of water equal

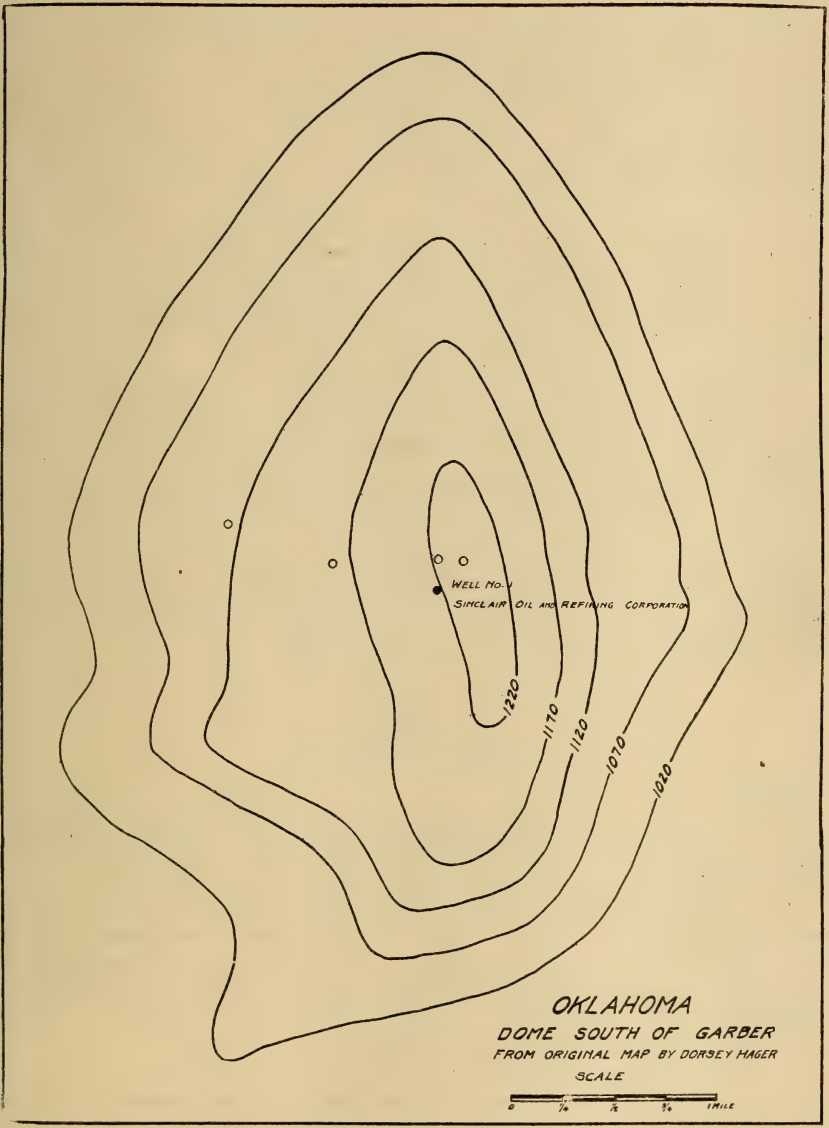
WELL No. 1
SINCLAIR OIL AND REFINING CORPORATION
1220
1170
1120
1070
1020
OKLAHOMA
DOME SOUTH OF GARBER
FROM ORIGINAL MAP BY DORSEY HAGER
SCALE
0
1/4
1/2
3/4
1 MILE

FIGURE 5.—*Structure Contour Map of Dome at Garber, Oklahoma*
From original surface survey by Dorsey Hager

to the depth of the wells; or, in other words, 43.4 pounds per square inch for each hundred feet of depth. The well pressure is usually somewhat more or less than this figure, due probably to the fact that the water saturation is not complete, or that gas pressures for other reasons are unusually strong. The gas pressure is evidently not entirely a reactive pressure against a water head. A well at Cushing 2,600 feet deep gave a gas pressure of 1,120 pounds; figuring the theoretical hydrostatic pressure of 43.4 pounds per hundred feet, gives 1,128.4 pounds. A well near Claremore, at a depth of 860 feet, gave a pressure of 375 pounds; the theoretical pressure as above calculated is 373.2. A well near Collinsville, at a depth of 1,100 feet, gave a pressure of 495 pounds; the theoretical head at this depth is 477.4 pounds. These were closed pressures on new wells taken by the Oklahoma Natural Gas Company. In contrast to this uniformity, Haworth reports a well in Kansas, 1,000 feet deep, with a pressure of 250 pounds, while another well half a mile distant, at a depth of 900 feet, showed a pressure of 375 pounds.

The region around Bartlesville produces oil on various types of structure, including anticlines, domes, terraces, and the heads of synclines, all lying together over a broad area of folding; this fact, together with local hardening or tightening of the sands, gives a very irregular outline to the fields as contrasted to the sharper structures farther west, or in local districts of the eastern or southern portion of the main field. South of the Arbuckle Mountains at Wheeler, Madill, and Healdton, the petroleum and gas lie in an area of abundant water saturation, and consequently on well defined structures that show reversed dips.

Texas

GEOGRAPHIC DIVISIONS

The oil fields of Texas fall into two geographical divisions, namely, those of the Gulf Coast and those of central and northern Texas, the latter being classified with the Mid-Continent region (see figure 6).

The several oil and gas fields of central and northern portions of Texas lie in districts rather widely separated. The production is controlled by distinct and rather sharply outlined local anticlines, domed terraces, and monoclines, with their surfaces lying at various stratigraphic horizons.

STRATIGRAPHY

The oil and gas sands are found at levels ranging from the Strawn group of the Pennsylvanian system up to the Taylor marls of the Upper Cretaceous. Positions of the various fields with respect to the stratigraphic boundaries are shown on the accompanying map and the horizon of the various sands are shown in the following general section.

The general stratigraphic section in northern Texas, given in descending order, is as follows:

	Feet
Tertiary system (Eocene).	
1. Cook Mountain and Mount Selman. (Saint Maurice of Louisiana, Claiborne.) Consists of clays, clay-iron conglomerates, and calcareous glauconitic beds.	
2. Wilcox group. (Sabine formation.) Sands, clays, and conglomerates with beds of lignite	400– 500
3. Midway group. Chiefly clays with some limestone	200– 300
Upper Cretaceous (Gulf series).	
1. Navarro group. Clay marls and glauconitic sands	400– 700
2. Taylor marls group. Beds of clay and sandy to calcareous, soft shale, with local lenses of sandstone. Contains Nacbatoch gas sand of Caddo field, oil sands of Corsicana field, and oil-bearing igneous rock of Thrall field	200– 500
3. Austin group. (Annona chalk and Brownstown marl.) Contains some oil and gas in Caddo field	200– 600
4. Eagle Ford group. Chiefly clays containing the Blossom oil sand of Caddo field	150– 400
5. Woodbine sand. Massive, soft sandstone with some shale. Main oil sand of Caddo oil field. Occupies approximate time interval of Dakota sandstone in New Mexico and northward into Canada. Also the Tamasopa limestone of the great oil fields in Mexico	50– 100
Lower Cretaceous (Comanche series).	
1. Washita group. Impure limestone with beds of shale and marl. Contains important water sand locally at Paris, Texas; includes, in descending order, the Pennington limestone, Bokchito formation, Caddo limestone, and Kiamichi formation (Denison, Fort Worth, and Preston formations)	175– 400
2. Fredericksburg group. Massive white limestone beds, including the Goodland limestone (Edwards limestone and Walnut formation)	25– 200
3. Trinity sand. Contains the oil of the South Bosque field in top member (Paluxy)	200– 400
Permian series.	
1. Double Mountain group. Sandstone, limestone, sandy shale, red and blue clays with beds of gypsum and salt	1,900–2,100
2. Clear Fork group. Thin-bedded sandstone, magnesian and carbonaceous limestone, red and blue clay-shale and irregular beds of cemented clay-iron concretions. Some gypsum	1,900–2,000
3. Wichita group. Sandstone of various colors. Red and bluish clay-shale and beds of clay-iron concretions or "Mud-lump conglomerate." Beds of limestone rare east	

	Feet
of Baylor County. Correlates with limestone and shale series known as the "Albany formation," in Baylor County, Texas	1,250–2,000
Pennsylvanian series.	
1. Cisco group. Sandstone, limestone, beds of gray sandy shale, dark colored gray shale and conglomerate. Contains coal 7. Includes upper oil and gas sands in Petrolia and Electra fields	800– 900
2. Canyon group. Sandstone, dark-blue shale, conglomerate, coal, and beds of massive escarpment forming limestone. Includes lower oil and gas sands in Electra and Petrolia fields	800– 950
3. Strawn group. Sandstone, clay, carbonaceous shale, and chert conglomerate. Includes Millsap formations, or beds for 1,000 feet below coal number 1. Contains oil and gas sands in Strawn, Moran, and Brownwood fields	950–3,700
(Unconformity.)	
4. Bend group. Mississippian? Hard blue limestone with blue and black shale. Occurs only in central coal field.	350– 375
(Unconformity.)	
Silurian, Ordovician, and Cambrian limestone.	

As a rule the oil and gas sands in the Pennsylvanian series of the northern Texas fields are similar in nature to those of the main fields in Kansas and Oklahoma; they are sandstones of a light to dark gray color, with a porosity varying from 10 to 25 per cent. They lie interbedded with more or less carbonaceous shale, as do corresponding sandstones in the fields of the Mid-Continent region farther north. The Nacatoch, Blossom, and Woodbine sands of the Caddo field (Texas-Louisiana) lie in the Upper Cretaceous series, as do the sands at Corsicana. The Lower Cretaceous, or Comanche series, includes at its base the Trinity sand which furnishes the oil in the South Bosque field. These sands of the Cretaceous are naturally not so hard as the strata of the older Pennsylvanian and, together with all the intermediate beds, are drilled by the rotary system.

Certain Texas fields have been well described by E. W. Shaw and George C. Matson in Bulletin Number 609 of the United States Geological Survey, entitled "Natural Gas Resources of Parts of Northern Texas." Matson states that the Nacatoch sand in the Mexia-Groesbeck field is a light gray, fine quartz sand, carrying many dark grains of glauconite. Tests by C. E. Van Orstrand, of the Geological Survey, from examples submitted by Matson, showed an average porosity of 25.5 per cent. This figure is probably a fair average for the Cretaceous sands of this region. The oil-bearing formation in the Thrall field occurs in a vesicular, soft, green serpentine, found in the Taylor marls at a depth of 850 feet. From

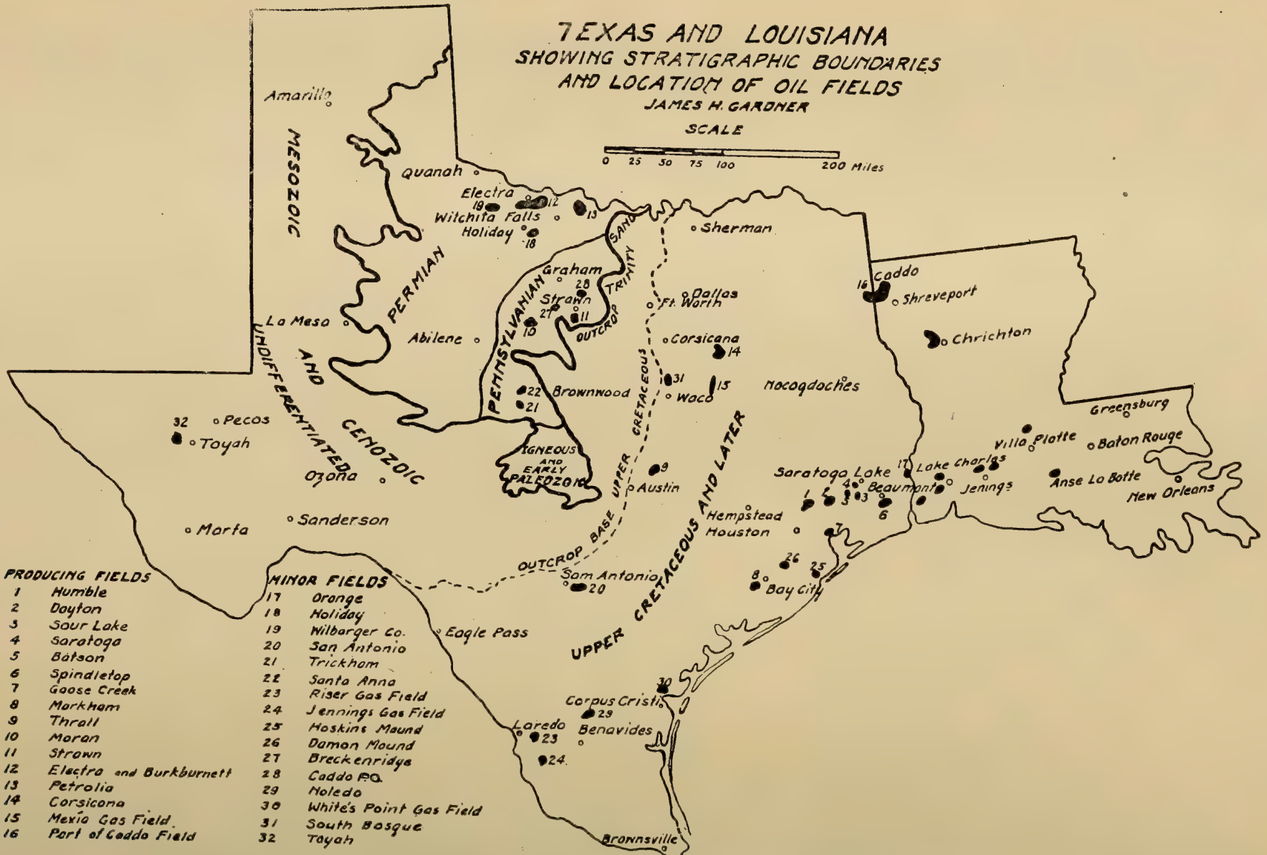
TEXAS AND LOUISIANA
SHOWING STRATIGRAPHIC BOUNDARIES
AND LOCATION OF OIL FIELDS
JAMES H. GARDNER
SCALE
0 25 50 75 100 200 Miles
MESOZOIC
PERMIAN
PENNSYLVANIAN
UNDIFFERENTIATED AND CENOZOIC
IGNEOUS AND EARLY PALEOZOIC
TRINITY SAND OUTCROP
OUTCROP BASE UPPER CRETACEOUS
UPPER CRETACEOUS AND LATER
Amarillo
Quanah
Electra
Witchita Falls
Holiday
Graham
Strawn
La Mesa
Abilene
Brownwood
Pecos
Toyah
Ozona
Sanderson
Marfa
Sherman
Dallas
Ft. Worth
Corsicana
Waco
Nacogdoches
Austin
Hempstead
Houston
San Antonio
Bay City
Eagle Pass
Laredo
Corpus Cristi
Benavides
Brownsville
Saratoga
Lake
Beaumont
Caddo
Shreveport
Chrichton
Lake Charles
Jenings
Villa Platte
Greensburg
Baton Rouge
Anse La Butte
New Orleans
PRODUCING FIELDS
1 Humble
2 Dayton
3 Sour Lake
4 Saratoga
5 Batson
6 Spindletop
7 Goose Creek
8 Markham
9 Thrall
10 Moran
11 Strawn
12 Electra and Burkburnett
13 Petrolia
14 Corsicana
15 Mexia Gas Field
16 Part of Caddo Field
MINOR FIELDS
17 Orange
18 Holiday
19 Wilbarger Co.
20 San Antonio
21 Trickham
22 Santa Anna
23 Riser Gas Field
24 Jennings Gas Field
25 Hoskins Mound
26 Damon Mound
27 Breckenridge
28 Caddo P.O.
29 Noledo
30 White's Point Gas Field
31 South Bosque
32 Toyah

FIGURE 6.—*Geologic Sketch Map of Texas and Louisiana, showing Locations of Oil and Gas Fields*

the latter portion of the time during which the Austin group was laid down and extending into the period of Taylor marls deposition there was considerable volcanic activity in this part of Texas. It resulted in the limburgite and basalt intrusions of Pilot Knob and other districts. At this time there were flows of lava which were possibly in part pyroclastic, and submarine, in nature; other igneous bodies are in part sill-like and appear to have been intruded laterally into the soft, unconsolidated beds of the newly deposited sediments. In the Thrall field the upper surface of this igneous rock is arched so as to give the general effect of an anticline or dome of small dimension. This condition has permitted water to hive up or concentrate petroleum in the porous body of the serpentine, thus presenting an occurrence of oil which is quite unusual in its nature.

While the oil and gas sands of the Cretaceous series are practically everywhere saturated with an abundance of water, this condition is not so generally true of the sandstones in the Pennsylvanian series. A number of wells in search of petroleum in the latter strata have found the salt-water saturation rather slight, and this fact, taken together with the probability that the amount of the original carbonaceous matter was in some territories somewhat meager, augurs badly for an abundance of petroleum in the southern portion of the Pennsylvanian area in Texas. Reconnaissance work by numerous petroleum geologists shows, also, that typical oil-bearing structures are somewhat restricted in this region; the sedimentary rocks are not so generally folded as those of the Mid-Continent region in Kansas and Oklahoma.

STRUCTURE

Back of any general view of the local structural features in northern Texas one must consider the broader phases of earth movements that have warped the strata over an extended territory. The oil and gas fields lie in a region between the Arbuckle-Wichita Mountains of southern Oklahoma on the north and the Llano-Burnet uplift in central Texas on the south. At several different periods of geological history strong forces were brought to play on the surrounding sedimentary strata of each of these areas, and it is more than likely that the periods of movement in the two cases were coincident. The result of such stresses has been the folding of the formations at different points, and where the other factors of oil and gas accumulation occur in harmony with them, important producing fields have been, and will continue to be, found. The oil field at Electra, for instance, is one of the most dependable in the whole Mid-Continent region. The area of saturated oil sands is large, the field does not decline rapidly, and the grade of oil is well up toward the best of the entire province.

The nature of the rock folding in Texas was different from that of the oil regions of Oklahoma and Kansas, in that the total stratigraphic section of the rocks in Texas was sufficiently competent to withstand in a large degree the forces that reacted on them. The local structures lie in widely separated localities rather than being bunched together irregularly, such as is characteristic of the main fields of eastern Oklahoma and Kansas to the north. Either the sedimentary beds in Oklahoma and Kansas were less able to resist the tectonic forces acting against them or else the disturbances in the Arbuckle and Ozark regions were more far reaching in their effects than those of the Llano-Burnet uplift.

In the Pennsylvanian area of Texas the rocks dip westward at an average rate of about 20 feet per mile. It is rather unusual to find a local area where there has been sufficient vertical movement to reverse this dip. The oil-bearing structures at Moran, Strawn, and Corsicana are essentially terraces, although they contain a few closing contours of ten feet interval. This condition is typical of a large portion of Electra and Burkburnett districts, but the Petrolia field and that of Mexia, for example, show anticlinal conditions which are more pronounced, as illustrated by the accompanying contour sketch of the Petrolia field (see figure 7).

As described by Shaw, the central portion of north Texas shows a broad "upwarp" or low geanticline, with its axis lying in a north-south direction, from which the Pennsylvanian strata dip westward, while on the east flank the unconformable sediments of the Cretaceous dip eastward. Whether or not beds below the Cretaceous dip eastward to conform with the younger formations is not known, nor has the actual presence of the Pennsylvanian strata on the east side been determined. The fact is demonstrated, however, that the Cretaceous strata follow the general structure of the older formations on the west flank. While these younger beds on the east flank outcrop west of Fort Worth and the projection of their horizon westward carries above the surface over the area of the Pennsylvanian and Permian, they appear again and lie at a low surface level in the Panhandle region; so it appears probable that a post-Cretaceous movement acted along the axis of an older structure, thus producing a broad geanticline over a broad area lying between the Arbuckle-Wichita region of Oklahoma and that of the Llano-Burnet region of Texas. The latter has been described by Sidney Paige in Folio Number 183 of the United States Geological Survey. This condition would possibly explain the fact that such a broad area of the outcropping strata is not folded into subordinate structures; probably the stresses from the two regions of maximum movement were to a notable extent relieved by the general rise of the intervening strata. This broad, low arch in central Texas is perhaps related in origin, as it is in size and form, to the Sabine uplift in northern Louisiana, which lies directly to the east. There is a well defined, broad structural basin between the two uplifts, in which lie the deposits of the Cretaceous and Tertiary systems. The Caddo oil field is situated on the north side of the Sabine structure.

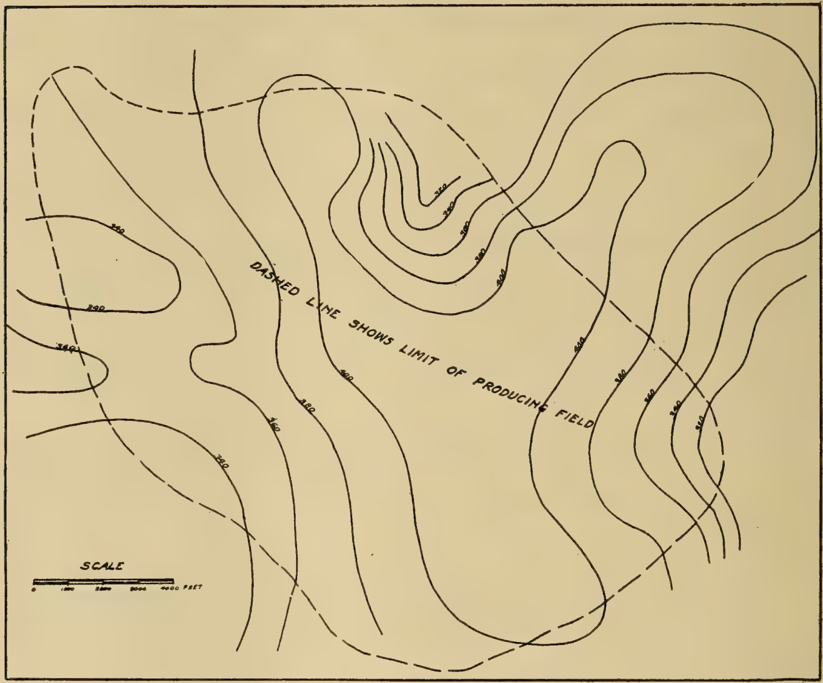

Figure 7.—*Structure Contour Map of Petrolia Oil and Gas Field, Texas*

From Bulletin 623, United States Geologcial Survey

The oil in the Toyah field, in the extreme western portion of Texas, is found in the Delaware Mountain limestone member of the Permian, which series is covered by the Washita group of the Comanche series. C. A. Fisher has stated that the oil occurs on a monocline dipping 5 to 7 degrees eastward; hence it seems probable that this region lies beyond the effects of the earth movements above mentioned and is related to compressive stresses that were initiated farther to the west, and have shown a tendency to adjust themselves by an eastward thrust along the west flank of the main basin, which is defined on the east by the Ozark, Arbuckle-Wichita, and Llano-Burnet uplifts, and on the west by the Rocky Mountains.

LOUISIANA

LOCATION OF THE FIELDS

The main oil and gas district of the Mid-Continent region in Louisiana is just north of Shreveport and is known as the Caddo field, from its position in and around Caddo Lake. This field has been described by G. D. Harris in his report on oil and gas in Louisiana Bulletin Number 429 of the United States Geological Survey. It has been more recently covered in detail by George C. Matson in Bulletin Number 619 of the Survey, and to these reports the reader is referred for more complete data regarding details of this district.

The Crichton or Naborton oil and gas field which lies south of Shreveport, in De Soto and Red River parishes (counties), is a recent discovery as compared to the Caddo field. It is closely related to the former field, however, in that it occurs on a fold subordinate to the larger Sabine uplift and produces oil and gas from approximately the same horizons as the former district.

STRATIGRAPHY

The main oil horizon in this territory is the Woodbine sand at the base of the Upper Cretaceous or Gulf series. It lies at a depth of 2,300 to 2,600 feet. The accompanying general section will show the stratigraphy of the oil region in the north portion of the State and the positions of the oil and gas sands.

The general stratigraphic section in oil region of northern Louisiana, in descending order, is as follows:

	Feet
Quaternary system.	
Red and gray sand, loam, clay, and gravel	0– 50
Tertiary system (Eocene).	
1. Saint Maurice formation. (Claiborne) Clays, clay-iron conglomerate, and calcareous, glauconitic beds	50–100
2. Wilcox group. (Sabine) Clays, sands, and conglomerate with beds of dark shale and lignite	400–500
3. Midway group. Chiefly clays with some limestone	200–300
(Unconformity.)	
Upper Cretaceous (Gulf series).	
1. Arkadelphia clay. Dark, stiff clays	300–600
2. Nacatoch sand. (Gas rock) Shreveport or Caddo gas sand	100–130
3. Marlbrook marl. Blue to dark marl, with chalky layers. Contains Saratoga chalk member	150–700

	Feet
Upper Cretaceous (Gulf series).	
4. Austin group. Contains at top the Annona chalk, 100 feet, and at base Brownstown marl composed of clay, chalk, and sand	200–520
5. Eagle Ford clay. Contains at top the Blossom oil sand. Bluish and carbonaceous clay with hard layers of limestone	350–400
6. Woodbine sand. Main oil sand of field at Caddo and at approximate position of Naborton sand	20–100
Lower Cretaceous (Comanche series).	
1. Shale, limestone, and lenses of sandstone. Denison formation (250–300). Limestone. Fort Worth (15–30). Shale and thin limestone. Preston (150–250)	415–580
2. Fredericksburg group. (Goodland limestone)	25– 50
3. Trinity sand. Largely untested in Louisiana, but contains oil sand at Madill, Oklahoma, and in South Bosque field, Texas	200–400

As will be seen from the above section, all the oil and gas bearing strata to date in this territory lie in the Upper Cretaceous series. The Nacatoch gas sand is light gray to drab in color and contains thin laminæ of clay; locally the sand contains lime and is occasionally rendered entirely impervious to water and gas by a cement of calcium carbonate; but this condition is very exceptional. It contains some grains of glauconite, a constituent characteristic of many of the sands in deposits of the Gulf series and Tertiary. The Blossom oil sand (at 1,800 feet in the Caddo field) is a quartz sandstone, usually soft, but sometimes indurated and containing lenses of clay. The Woodbine sand, or the main oil sand of the region, is a porous quartz sand, containing argillaceous, ferruginous, and glauconitic material, together with an abundance of carbonaceous plant remains.

The Arkadelphia clay, the Marlbrook marl, and the Eagle Ford clay all contain organic material, chiefly in the form of dark to black carbonaceous clay or shale. The Nacatoch sand, the Annona chalk, which contains some oil and gas, and the Woodbine sand lie in alternate positions with these deposits. The clays are impervious to the passage of oil and gas and hence restrain those materials in the porous sands, notwithstanding the fact that the oil and gas are under tremendous initial pressure.

STRUCTURE

The Sabine uplift is a broad, flat-topped, irregularly shaped arch in the sedimentary beds which, on the south, shows a relatively steep downward dip. Veatch, in his excellent report on the Geology and Underground Water Resources of Northern Louisiana and Southern Arkansas, termed this steep zone the Angelina-Caldwell Monoclinal Flexure (Professional Paper Number 46, United States Geological Survey). On the north the uplift is partially bounded by a somewhat narrow and sharp syncline, from which the strata rise again northward to the Red River-Alabama Landing fault. Veatch draws the probable extension of this fault from the Red River Valley north of Sherman, Texas, all the way across northern Louisiana to a crossing of the Mississippi River north of Vicksburg, Mississippi, where it intersects with the Angelina-Caldwell monocline. There is strong structural evidence that this fault, or flexures coincident with it, extends across south-central Mississippi through Jackson and thence into southern Alabama. The strike of the fault above mentioned lies more or less parallel with the Arbuckle-Wichita Mountains, and the extension westward of this line of disturbance along the Red River Valley would coincide roughly with the long anticline mapped

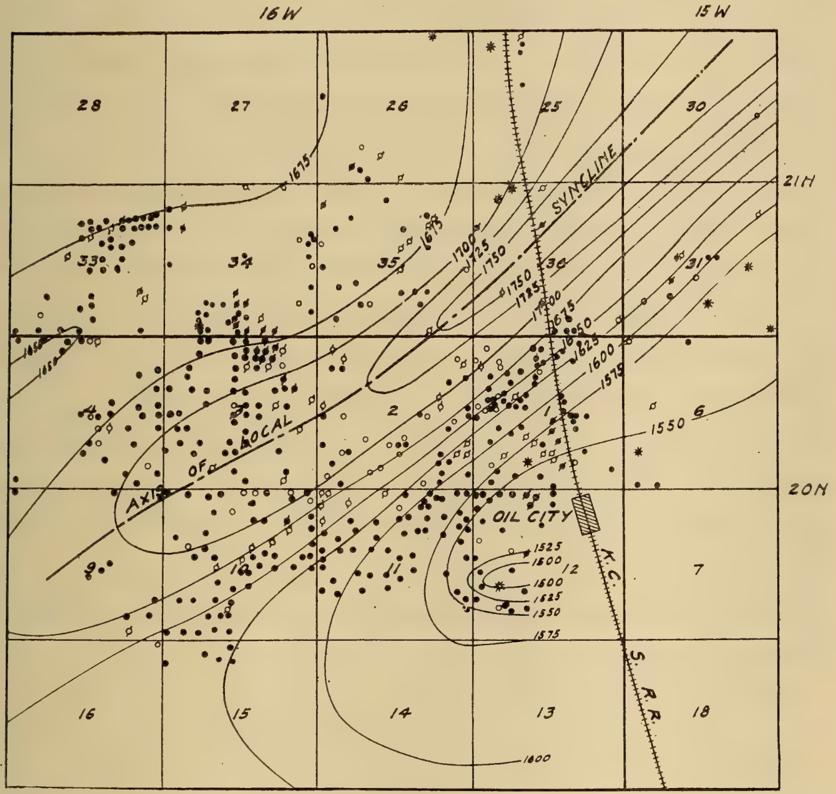
16 W
15 W
21 N
20 N
28
27
26
25
30
33
34
35
36
31
4
3
2
1
6
9
10
11
12
7
16
15
14
13
18
SYNCLINE
AXIS OF LOCAL
OIL CITY
K. C.
S. R. R.
1675
1700
1725
1750
1650
1625
1600
1575
1550
1525
1500
1400

FIGURE 8.—*Structure Contour Map of a Portion of Caddo Oil and Gas Field, Louisiana. Numbered below Sealevel on Blossom Sand*

From Bulletin 619, United States Geological Survey by Munn in the Grandfield district of southern Oklahoma (Bulletin 547, United States Geological Survey). But the Angelina-Caldwell monoclinal flexure lies in a northeast-southwest direction roughly parallel to the Gulf coast and is possibly related to parallel fault zones in connection with the saline domes of the coast oil fields.

Thus it appears evident that the two lines of structure are the results of different orogenic movements. The Sabine uplift lies between the two convergent lines of disturbance and has its present structural form as a result of stresses acting on it at more than one geological period. Certainly one of the principal movements was in the later Tertiary. Veatch calls attention to the fact that more recent displacements along the fault have involved the Pleistocene deposits adjacent to the Ouachita River just above Alabama Landing. These recent movements far to the north suggest that the stresses that initiated the uplifts in the form of saline domes and faults along the coast were expressions of a compression that was of a regional nature.

Local structures, such as those that characterize the oil fields in the Caddo and Crichton districts, are not of the saline dome type, but are small folds due to crumpling of the strata on the larger uplift (see figure 8). Matson calls attention to the fact that the local anticlines at Caddo show cross-folding, and that the axes which lie northeast and southwest are older than those which cross them from northwest to southeast. It is interesting to note that these two lines of folding lie roughly parallel with the two major lines of structural movement above mentioned, and that the more recent of these small folds are parallel with the recent faulting in the northwest-southeast direction along the fault near Alabama Landing.

Origin of the Petroleum and Natural Gas

It seems practically inevitable to the writer that any geologist who comes to be familiar with the occurrence of oil and gas in the Mid-Continent field must sooner or later take the view that these substances have originated from strata of hydro-carbon bearing shale; such deposits lie within or inter-stratified with the sandstone beds or other porous rocks that contain the accumulated deposits. We are practically forced to this theory of oil origin by a process of exclusion. With the present limited store of facts regarding the original source of petroleum and its associated gases, it is scarcely possible to select any theory other than the above mentioned without having arrayed against it a mass of facts with which it is entirely inconsistent. Marius R. Campbell has stated in his historical review of theories that during the past fifty years chemists and geologists have been actively endeavoring to solve the problem of origin of these natural liquids and gases, but that to date most of the hypotheses have proved to be merely speculations. He cites the work of Arnold, Anderson, and Johnson on the McKittrick-Sunset oil region of California as being exceptional in this country, in that they seem to have discovered in that case the actual origin of the petroleum, the same being from diatomaceous and foraminiferal material deposited in beds of marine shale.

One is safe in assuming that the origin of petroleum in any one field may be entirely different from that in some other portion of the globe; but we do not take so much latitude in viewing the origin of other hydrocarbon compounds—as, for instance, coal. It is a generally accepted fact that coal is of plant origin the world over, yet it is also a complex combination of varied chemical nature, having gone through various changes in its transformation from lignite to anthracite. In the metamorphism of coal it has thrown off its volatile hydro-carbon compounds to be diffused through the adjacent rock strata until the percentage of fixed carbon in the remaining material is at its maximum. But coal was deposited originally under special physiographic conditions, unquestionably being the accumulated debris from plants that grew in swampy grounds, and were buried in shallow water, where they were subject to more or less immediate transformation and loss of volatile materials. But other plant remains drifted out to deeper waters or into the sea, probably in a colloidal state and interlocked with clay, so that they finally rested on the floor of the water body as carbonaceous deposits.

A. V. Bleininger and others have shown that a solution of water containing the organic substances from the distillation of plants, such as straw, will produce a colloid with clay so that it will remain in suspension; but the clay will again be thrown down on contact with salt water. This has unquestionably been an important factor in the deposition of clay deposits around the margin of bodies of marine and brackish water—as, for instance, the clays of the coastal plain deposits, which represent the marginal sediments of formations not yet entirely raised above the ocean floor. There is a deposit of natural tarlike coal in the San Juan Basin near Seven Lakes, and also north of San Mateo, New Mexico, which is colloidal in nature. If blunged with water, it will remain in suspension as a black fluid until the water is evaporated or until otherwise precipitated. This is cited as an instance in nature where carbonaceous material is colloidal, not having had its nature changed by contact with other compounds. Collodial matter from decaying leaves is a familiar coloring agent in concentrated water pools, and unquestionably an enormous amount of hydro-carbon compounds have in this manner found their way in the course of geologic time to areas of deposition. Imagine what an enormous area was covered by the deposit of carbon-bearing material that formed the famous Pittsburgh coal bed. Waters drained from such a region at the time the plants were undergoing their first stage of decomposition and mechanical destruction must have carried fine clay and were probably black with the sediments of plant debris.

The carbonaceous elements of the black shale beds have been subjected to a long period of natural distillation in the buried sediments such as characterize the Mid-Continent oil and gas fields. It is believed that these shale beds have supplied the contributing material of the petroleum and natural gas accumulations throughout this region, regardless of the geological horizons in any particular district. Shale containing more or less carbonaceous matter is common in all the formations from the Mississippian series up to the youngest oil-producing beds of the Cretaceous, or even in the later Tertiary sediments of the Gulf coast.

The Accumulation of Petroleum and Natural Gas in the Mid-Continent Fields

There are certain principles in the accumulation of oil and gas that are alike applicable to all producing fields in the Mid-Continent region. While it is recognized that here is one of the most perplexing subjects with which the petroleum geologist has to deal and one that would be of great practical value if clarified in its entirety, still there have been recent contributions to the subject that are advanced steps of great importance. There are two American authors in geology who have recently brought forward ideas based on physics that are destined, in the writer's opinion, to remain classic milestones along the highway of approach to a final understanding of the subject. One is M. J. Munn, who has set forth reasons why the old application of the anticlinal theory must be altered, and has laid stress on the importance of hydraulic forces which accompany moving bodies of water in the underground rocks; the other is Chester W. Washburne, who has discussed the effect of capillary movements due to the difference in surface tension of water, gas, and petroleum. These principles have surely played important rôles in accumulation.

Petroleum and gas were originally diffused through certain strata and have later been gathered into "pools" of commercial size. In this connection, the writer believes, the simple effect of early consolidation due to pressure of overlying sediments has not received the attention due it.

In the Mid-Continent field there is no evidence that the present containing strata (the sands) are the original sources of the petroleum and gas; but on the other hand they are probably the porous bodies to which these substances have been caused to migrate. It is believed that consolidation of carbonaceous shale beds, with the resulting reduction in the total amount of their pore space, due to compression of the rock into a lesser volume, has been an important factor in initiating the concentration of the natural hydro-carbon distillates.

In the early geological history of the carbonaceous beds, pressures that changed them from clay to shale so reduced their volume that a movement of their liquid contents, including hygroscopic, or connate water, together with the liquid hydro-carbon compounds and gases, took place. In reality this was a combination of distillation and concentration in which the greater surface tension of water must have played an important part in pushing the oils to the areas of greater porosity and thus beginning the migratory movement to the nearest beds of sandstone. Most carbonaceous shale will furnish some oil by destructive distillation, and when one considers the slow exertion of pressure during a long period of time, in which water moved through the shale, effects similar to general distillation may have been produced. It is true that such migration would have a tendency to fractionate the oils except for the fact that they have been moved by hydraulic force through pores already containing water, and the results thus obtained might differ from fractionation by adsorption of petroleum through dry shale or fullers' earth. In postulating such migration it is plausible to consider that it was in upward and lateral directions, which were usually those of least resistance, and involved a great thickness of rocks in the time of their youth. In the sandstone beds water moved on into the finer pores of the overlying shale, as well as laterally toward the outcrop.

A cross-formational movement of fluids of the character above mentioned would ultimately come to equilibrium, so far as the pressure is concerned, after the deposits were sufficiently compressed or metamorphosed to support the overlying load of superimposed strata. Further movement would result from capillarity alone, water passing into the fine pores of the overlying shale, but small amounts of oil and gas remaining behind. The dryness of some beds of sandstone may be explained by the process of capillary absorption of water into adjacent shale.

The oil and gas sands that now lie at drillable depths were formerly, in many cases, buried under thousands of feet of overlying beds. Munn has pointed out the fact that the deeper a sand lies, beyond certain limits, the more likely it is to be non-saturated with water. In such a case, if a sand originally contained salt water and subsequently lost it, what was the source of the present salt water in the sands around the oil and gas fields? In this connection the writer leans to the possibility that the present water is meteoric water; that it has come into the beds from their outcrop at the surface, working its way inward and downward through the long period of time that has elapsed since crustal movements produced the local structures and subsequent erosion brought the beds to outcrop relatively near them. The loss of original connate water by capillarity would leave more or less salt in the dry sands which the meteoric waters would again absorb and become themselves salty.

Water moving down the dip under a gradually increasing head would gather the oil and gas that remained distributed through the sand and push it forward and downward. At a local structure gas and oil traveling ahead would be caught until the moving water completely closed around the ends of the structure so as to completely trap the deposits from farther movement; water would hold them under hydrostatic head, and in the case of gas force its absorption, so far as possible, in the petroleum. In the case of only a partial saturation by water and slight head, the oil and gas accumulations would not be perfectly gathered nor held sharply under the structures, but the accumulations would lie on milder types of folds, such as terraces and the heads of synclines, with gas more definitely separated from the petroleum. Far down the dip, where the hydrostatic head is strong, and consequently the saturation more complete, only the reversed or closed structures, such as domes or anticlinal bulges, would be sufficient to stop the onward movement of oil and gas. It is true in the Mid-Continent field that the deep sands produce only in structures that show closed structure contours. The fields farthest to the west in Oklahoma and Kansas, particularly where the sands lie at depths below 1,800 feet, are situated on domes or bulges and the surrounding portions of the sand are strongly saturated with brine. Still farther down the dip the writer predicts that the oil sands will eventually be found free from water, and that at some point between the producing fields and the dry region there are relatively narrow, meandering lines of petroleum and gas lying along the strike at the lower side of the saturation. Here and there they may be encountered by a well, but they are winding in shape like irregular coast lines, and too narrow to be followed out profitably with the drill. The quantity of oil thus concentrated would depend on the loss higher up the dip, also on the amount of original oil in the rocks. In the case of movement down the dip across a great number of local structures the amount of oil pushed on ahead would be relatively small, due to its having been previously collected from point to point. But the ideal condition for a big field is that of a large closed structure lying relatively far, but not too far, down the dip of good oil-bearing beds, without other areas of catchment close above it, and having a long plunging axis extending along the strike line so as to subtend large areas of catchment. Such a field should also include a thick porous sand.

Four important Factors

Throughout the Mid-Continent region it is evident that the original supplies of oil and gas were localized. Splendid structures in some districts fail to furnish commercial fields, due to lack of sufficient material from which oil had its origin. Generally speaking, there are four factors that must work together in harmony in this region in order to make an oil field in any particular district. They must be:

1. A porous bed or "sand" in which oil may be absorbed.
2. A suitable structural condition to permit concentration at a particular locality.
3. Presence at one time or another of more or less water as the accumulating agent.
4. Petroleum originally diffused through the rocks within a reasonable area surrounding the structure.

The commercial value of an untested structure in the Mid-Continent region depends not alone on its size and form, but also on the relation it bears to these other conditions. Some local folds do not produce fields because of the absence of sands; others show dry sands containing very small quantities of oil, but indicating that no water body has lain within or moved through them to concentrate the oil. Others show sands with salt water alone, there having been no oil or gas for it to concentrate within the structures. Carbonaceous shale beds are usually of local extent, and just so the original supplies of petroleum and gas in the rocks were confined to certain districts. In most cases oil and gas have been moved in limited and disconnected bodies. Local structures that lie in districts where there are good open beds of persistent sandstone containing an abundance of salt water and lying adjacent or near to thick beds of persistent, black carbonaceous shale (such as the Bartlesville sand in the Cherokee shale) are the ideal ones that, coupled with man's endeavors, have brought fame to the Mid-Continent fields.

Quality of the Petroleums

The average crude petroleum in Kansas and Oklahoma is dark green in color by reflected light, brownish by transmitted light, and has a Baumé gravity of about 34 degrees. Certain districts, as, for instance, Muskogee, furnish oils that are yellowish green in reflected light, or bright wine color in transmitted light, and run as high as 38 degrees Baumé gravity. A further example of superior grade petroleum is that of the Madill field, Oklahoma. This has a dark olive color in reflected light, or dark wine in transmitted light, and runs as high as 47.5 Baumé gravity. From Garber and Ingalls are obtained green oils of 43 degrees Baumé gravity. As examples of petroleum of slightly inferior grades may be mentioned that from the Healdton field, Oklahoma, which is a very dark oil, with an average Baumé gravity of about 30 degrees, and runs somewhat low in its content of light distillates. Petroleums from the deeper sands, as at Cushing and Blackwell, Oklahoma, or at Augusta, Kansas, average between 35 and 40 degrees Baumé gravity and run relatively high in gasoline and other light products. Petroleums from the Petrolia and Electra fields, Texas, have a dark brown color in reflected light, and range from 39 to 45 degrees Baumé gravity, but are not so high in many of the light distillates as petroleums from Kansas and Oklahoma. Petroleum from the recently discovered Thrall field of Texas is rather light in gravity, and has a brownish color somewhat similar to the better grades at Corsicana and Moran, Texas, or at Caddo, Louisiana. Local areas in Texas, as, for instance, the Brownwood district, furnish petroleum running low in gravity and high in lubricating constituents, resembling in this respect oil from the Healdton field, although of lower gravity.

While the Mid-Continent petroleums are rarely free from asphalt, this constituent is in very small quantity, varying from zero to 5 per cent. The accompanying table of analyses will serve to give a general comparison of the different grades.

ANALYSES OF THE PETROLEUMS

Fields.	Baumé gravity.	Gasoline, benzine, naphtha, kerosene, 0–300° C.	Lubricating oil and residuum.
KANSAS			
Chanute	23.1	39.5	57.2
Paola	34.5	43	55.8
Augusta	38.3	53.6	46
OKLAHOMA			
Muskogee	38.1	46	52.8
Cushing	40.9	66	30
Bird Creek	34.8	45.5	52.8
Glenn Pool	35.5	50.5	49.9
Healdton	30.3	42	52.9
TEXAS			
Petrolia (deep)	44.9	35	65
Petrolia (shallow)	39.5	19	81
Electra (deep)	42.	28.5	71.5
Electra (shallow)	40.8	25	75
Corsicana (light)	36.3	50	50
Corsicana (heavy)	25.9	55 (kerosene)	45
Thrall	38.4	55	45
Strawn	36.3	51	49
LOUISIANA			
Caddo	41.	58	40.4
Crichton	39.8	67	33

NATURE OF LOCAL FOLDING

In the Mid-Continent region from Kansas to Louisiana there are local folds in the earth's strata in which the total area affected is very small for the amount of vertical movement. It is scarcely consistent to accept the theory of their having originated, as previously supposed, entirely from thrust pressures acting tangentially. For example, note the dome at Garber. This is a local uplift that lies west of all other known oil and gas fields in Oklahoma, and consequently farthest from the Ozark arch, yet it is above the average in height and confined to a relatively small area. It is a common type. The structures at Eldorado and Augusta, Kansas; at Cushing, Oklahoma, or at Petrolia, Texas, are all examples of domes, or anticlines, that lie back from the sources of pressure in regions that are otherwise very slightly disturbed by folding and faulting.

In this connection it is suggested as probable that the movement producing local folds of this type has acted from below, although it must not be understood that they are results of intrusives, nor that they are laccolitic in origin. But it is believed that the total thickness of the sedimentary strata are folded, the first yielding having been in the profound depths. This presupposes a deep-seated transmission of pressure through the zone of flowage.

In the case of mountain development such a flowage took place on a large scale. The crystalline rocks of the Ozark, the Arbuckle, and Wichita Mountains, the Llano-Burnet region of Texas, or of the Rocky Mountains, have risen from beneath the sedimentary series, due to isostatic adjustment on a large scale. At the time these major stresses were acting on the earth's crust the zone of flowage transmitted pressure more or less equally in all directions, so that the abysmal magma moved laterally to the region of least resistance; but in so doing the overlying rocks had to bear strong hydraulic forces acting upward, and at points where the total strength of the overlying section was not competent to withstand this pressure there was a local buckling of the whole lithosphere.

Well logs show that the folds of the Mid-Continent region do not grow less in strength with depth, but, on the other hand, the deeper sands show the sharpest dips. The Bartlesville sand at Cushing, Oklahoma, shows stronger structure at 2,600 feet in depth than does the Layton sand at 1,400 feet. Contours on the Tucker sand, below the Bartlesville, show the folds to be even stronger. In 40 feet of surface dip on a limestone at Augusta, Kansas, the oil sand at 2,400 feet in depth dips 80 feet. Similar conditions exist at Blackwell and Healdton, Oklahoma, and are in fact the rule rather than the exception throughout the Mid-Continent fields.

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PETROLEUM IN CANADA [1]

BY WILLET G. MILLER

(*Presented before the Society December 28, 1916*)

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PRODUCTION

Compared with the United States, Canada is but a small producer of petroleum, the output of the two countries for the year 1915 being about 281,104,104 and 215,464 barrels respectively. In other words, the production of Canada was less than one-tenth of one per cent of that of the United States. Preliminary estimates for 1916 are 198,123[2] and 292,300,000[3] barrels respectively. With the exception of a very small output in Alberta, Ontario and New Brunswick are the only provinces that are producing petroleum in commercial quantities. A little has been found in numerous places beyond the limits of the producing areas in the two provinces and elsewhere in Canada.

Owing to the comparatively small importance of the industry in Canada, and also to the fact that information concerning the distribution and modes of occurrence of petroleum in this country is in readily available

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[1] This paper is one of a series composing a "Symposium on the Geology of Petroleum." See this volume, p. 156.

Manuscript received by the Secretary of the Society March 31, 1917.

[2] Preliminary Rept. Min. Prod. Canada, 1916. Mines Branch, Ottawa, No. 449.

[3] Science, March 23, 1917, p. 290.

form, in recent government publications, the subject of this paper will be treated briefly.

The chief cause for the smallness of the production in Canada is due to the fact that much of the surface of the two largest and most populous provinces, Ontario and Quebec, about 70 per cent of the former and more of the latter, is occupied by rocks, the pre-Cambrian, in which petroleum is not to be looked for. Of later compact rocks only the Paleozoic are found in these provinces. In Ontario, the oldest and largest producer, the Paleozoic is not represented by strata younger than the Devonian. Hence in this province Paleozoic rocks are not only restricted as regards areal distribution, but as to thickness as well.

ONTARIO

ERIE-HURON PENINSULA

The most interesting fact, in connection with the petroleum industry of Ontario, is its persistence, production having been continued uninterruptedly for about 55 years in the only area, that of the Erie-Huron peninsula, from which the material is derived. It should also be added that the wells are comparatively shallow.

FIRST DEVELOPMENT

In 1859 or 1860 the first attempt was made at utilizing Ontario petroleum. The oil first used was that which made its way to the surface at Oil Springs, Lambton County. Later, surface wells, from 40 to 60 feet in depth, were dug through the soil. The first drilling in compact rock was done about the year 1861. During late years, in spite of the discoveries in other localities in the area, the production has declined.

STRUCTURAL FEATURES

Information concerning the structural features, such as anticlines, in the Ontario petroleum area is not great. Much of the area is covered with loose deposits and care often has not been exercised in recording drilling operations. Anticlinal structures were described as early as the beginning of the petroleum industry, and as they have been referred to by most writers on the field since that time, there is no need to deal with them here.[4]

OIL-BEARING FORMATIONS

According to various writers, oil has been found in Ontario in each of the following formations: Onondaga (Corniferous), Oriskany, Niagara,

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[4] Geology of Canada, 1863, p. 379.

Medina, and Trenton. It may be added that, owing to differences in nomenclature, there is more or less confusion in the age terms employed.

ONTARIO FIELDS

The following brief notes on the Ontario fields, compiled by C. W. Knight, give some of the chief characteristics:[5]

"LAMBTON COUNTY OIL FIELD

"The Lambton field has been producing continuously since 1862. In the first few months of its history a few of the wells yielded from 1,000 to 7,500 barrels daily; but at present, and for many years in the past, the average yield of a well is very small—probably 8 or 9 gallons a day. In 1905, for instance, E. T. Corkill noted a group of 100 wells which together were producing 150 barrels a month. It has been pointed out by T. W. Gibson that 'it is only the large number of wells, and the economy in management which long experience has taught the operators, that enables Lambton County to be reckoned among the oil-producing regions today.'

"The wells are located in the townships of Enniskillen and Moore—largely in the former, where are situated the towns of Petrolea and Oil Springs. The Petrolea field is the largest in area in the province, extending about ten miles northwest to southeast, with an average width of three miles.

"Oil occurs at a depth of 370 to 480 feet below the surface, and at 60 to 70 feet below the top of and in the Onondaga limestone.

"The deepest well in Ontario was drilled in 1915 in concession XI, township of Enniskillen. A depth of about 4,000 feet was reached without striking either gas or oil.

"TILBURY OR KENT OIL FIELD, KENT COUNTY

"Oil was first discovered in East Tilbury township in 1905. Two years later, in 1907, the production had risen to 411,588 barrels; but by the year 1914 it had fallen to 18,530 barrels.

"Oil occurs in the Tilbury field, which lies for the most part in East Tilbury township, and partly also in Romney and Raleigh townships, at a depth of 1,250 to 1,426 feet below the surface. According to Eugene Coste:[6]

" 'The two upper oil pays in the southern part of the field are found in the lower brown dolomites and gypsum of the Onondaga, while the lower oil pay is struck in the upper beds of the Guelph and Niagara. In the northern end of the field, north of the Michigan Central Railway, the lower beds of the Onondaga are barren of oil, which is there altogether found in the Guelph, but the gas is still found there in the lower beds of the Onondaga, in the strata which form the first and second oil pays of the south end of the field. In the east middle part of the field, on the other hand, the oil is struck in the Onondaga strata which constitute the gas pays in many of the wells of the middle western part of the field.'

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[5] Ontario Bureau Mines, vol. xxiv, part 2, pp. 10, 11.

[6] Jour. Can. Min. Inst., vol. x, p. 82.

"Bothwell Oil Field, Kent County

"While the production of oil in this field has been gradually failing, table number 1 shows that the Bothwell field in Zone township has been one of the steadiest producers in the province during recent years. According to E. T. Corkill,[7] the wells are shallow, averaging about 600 feet in depth, and the formations drilled through are very similar to the Lambton field. The oil in one of the wells occurs at a depth of 365 to 375 feet from the surface and at about 188 feet below the top of and in the Onondaga.

"Leamington Oil Field, Essex County

"In 1902 oil was discovered in this small and now abandoned field at a depth of 1,040 to 1,125 feet in a porous dolomitic limestone of the Guelph formation. In 1905 the Hickey number 4 had a flow of 1,200 barrels daily for the first three days, but it rapidly fell to about 200 barrels. The field is located in Mersea township.

"Dutton Oil Field, Elgin County

"Oil was struck in Dutton township about the year 1898, the production since being small. The oil occurs in the Onondaga, at a depth of 160 to 175 feet from the top of the formation.

"Onondaga Oil Field, Brant County

"The Onondaga oil field, named from the township in which it occurs, was discovered in 1910. According to G. R. Mickle,[8] the oil is found in the White Medina at a depth of about 550 feet.

"Thamesville, Belle River, and Comber Oil Fields

"These three fields have not as yet become important producers."

The only other area in Ontario that offers possibilities for the occurrence of petroleum in commercial quantities is that which borders on James and Hudson bays. This area is wholly unexplored, in so far as drilling operations for petroleum are concerned; but the railway to Port Nelson will soon be completed and the area will be rendered more accessible. It contains Ordovician, Silurian, and Devonian strata in much larger volume than the Erie-Huron area.

New Brunswick

The production of New Brunswick is comparatively insignificant. Beginning with 95 barrels in 1909, the production has never exceeded 2,700 barrels. In 1916 the quantity was 1,345 barrels.

The oil occurs in the Lower Carboniferous, in the Albert shale series.

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[7] Ontario Bureau Mines, vol. xiv, part 1, p. 90.

[8] Ontario Bureau Mines, vol. xx, part 1, p. 38.

In the St. Joseph oil field, now abandoned, the petroleum is found at a depth of 247 to 370 feet below the surface. In the Stony Creek gas and oil field the wells range in depth from 1,200 to 2,060 feet.

The Albert shale series contains the so-called oil shales, which yield, when retorted, 27 to 56 imperial gallons of crude oil and 30 to 110 pounds of ammonium sulphate per ton. The shales were worked more than forty years ago, but the cheaper oils of the United States and Ontario forced the works to close.

Of interest is the presence of "albertite," a solid bitumen representing the residuum of petroliferous seepages. It occurs filling fissures in the Albert series and in younger Carboniferous strata. The large vein at Albert mines was mined over a distance of half a mile to a depth of 1,100 feet, below which it became too narrow to pay. The vein was vertical and varied in width up to 15 feet. It was mined for thirty years, during which time 230,000 tons were produced having a value of $15 to $20 a ton.

F. G. Clapp's[9] conclusion concerning New Brunswick is as follows:

> "In general, it may be said that outside the developed oil and gas fields the borings so far made have not afforded, because of insufficient depth or poor localities, any real test whatsoever of the oil or gas possibilities within the province of New Brunswick. To be conclusive, new borings located in accordance with approved structural principles and carried to the Albert shales, or in their absence to the underlying crystalline or metamorphic rocks, will be necessary to establish the presence or absence of petroleum or natural gas."

ALBERTA

During recent years there has been considerable search for petroleum in the province of Alberta, but up to the present it has not been found in important economic quantities. A little oil of low specific gravity is produced near Calgary and a little has recently been found in the gas field east of Edmonton. It may be added, however, that large areas in Alberta and adjoining territories remain to be explored, and belief is strong that important oil fields will yet be discovered.

A region lying farther north is considered to be of great promise, as is shown by the following quotation from Charles Camsell:[10]

> "In the northern parts of the Great Plains also there are numerous evidences of mineral wealth, the most important being that of oil, springs of which have been noted on the shores of Great Slave Lake and at several points in the valley of the Mackenzie and on Peel River. It is estimated that the rocks which are the source of this oil, namely, the Devonian strata, are the surface

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[9] Petroleum and Natural Gas Resources of Canada, Dept. Mines, Canada, vol. 2, p. 57.

[10] Geog. Jour., Sept., 1916, pp. 254-255.

rocks of about 150,000 square miles of the lower Mackenzie basin, while in the southern part they extend under a larger area of younger rocks, so that their total area covers not less than 300,000 square miles. The future as regards oil, therefore, is full of promise and can not easily be estimated at its full value. The region is believed to be one of the largest areas of possible oil-bearing country yet unexplored on the face of the earth, and it is to the exploitation of the oil resources that we look for the greatest development in the basin of the Mackenzie River."

BIBLIOGRAPHIC REFERENCES

In concluding this brief description of the modes of occurrence and supplies of petroleum in Canada, it may be pointed out that detailed information on the subject is now in handy form, several important reports or compilations of literature on the subject having been published within the last two years. Ontario is dealt with in a report by Cyril W. Knight,[11] Ontario and Quebec by Wyatt Malcolm,[12] and the whole of Canada by F. G. Clapp and others.[13] Papers by D. B. Dowling, dealing especially with Alberta, should also be mentioned.[14]

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[11] Ontario Bureau Mines, vol. xxiv, part 2.

[12] The oil and gas fields of Ontario and Quebec. Geol. Survey Canada, Memoir 81.

[13] Petroleum and natural gas resources of Canada. Mines Branch, Canada, No. 291.

[14] Correlation and geological structure of the Alberta oil fields. Am. Inst. Min. Eng., vol. lii, 1915, pp. 353-362; also papers published by the Geol. Survey Canada.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 28, PP. 727-734 SEPTEMBER 30, 1917

LATE THEORIES REGARDING THE ORIGIN OF OIL[1]

BY DAVID WHITE

(Presented before the Society December 28, 1916)

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INTRODUCTION

Investigations as to the origin of petroleum have of late been characterized by the search for evidence bearing on the validity of old hypotheses more than by the proposal of new ones. In fact, the past five years—the period within which a theory may have retained its newness—have been marked by improvements of the old inventions rather than by discoveries and original patents. Mainly these improvements are the outgrowths of observations of the characteristics of the oil-bearing strata and their conditions of deposition; of the geologic structures in which oil pools are found, and, in particular, of the mutual relations of oil, gas, and water, and their reactions with one another; and finally, and most important, of capillarity, porosity, and solution. These more immediately profitable fields of inquiry have already been discussed.

FORMER THEORIES OF ORIGIN

The fissure separating the followers of the inorganic origin of petroleum from the organic remains open; but there are now comparatively few remaining on the side of origin from metallic carbides, Sokoloff's

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[1] This paper is one of a series composing a "Symposium on the Geology of Petroleum." See this volume, p. 156.

Manuscript received by the Secretary of the Society March 26, 1917.

cosmic theory,[2] Ross' solfataric gas hypothesis,[3] or Kizhner's theory[4] of the contact of hydrogen with red-hot carbonized iron in the depths of the earth. This theory, though apparently of independent origin, is anticipated in some respects by the synthetic experiments by Steiger. The laboratory synthesis of hydrocarbons is the subject of an excellent brief discussion by Bacon and Hamor. Chemically all are possible; geologically they are, in brief, totally incompatible with obvious facts, and therefore, from present standpoints, impossible. The adherents to the inorganic origin are nearly all chemists. Practically all geologists are in opposition. The latest blow to the inorganic origin has been struck by a chemist distinguished for his researches in petroleum. Mabery points out[5] that the nitrogen derivatives which are present in most, if not all, petroleums are conclusive evidence of the inorganic origin of the oils, since they can have been derived only from matter of organic origin.

Modern Theory of Origin

On account of both the geographic and the stratigraphic distribution of the petroleums, their optical characteristics, and the conditions under which the organic mother detritus seems in most cases to have been deposited, it is now generally believed that petroleum is derived for the most part from plants of low orders, yielding waxy, fatty, gelatinous, or resinous products, with which is mingled more or less animal matter, possibly associated in plankton. However, it is thought by many that animal organisms, such as foraminifera, may have been the principal source, at least in some instances. This plant and animal matter was deposited as organic detritus or debris in muds and slimes, including the "sapropel" of Potonié; in the bottoms of ponds, lakes, estuaries, and under favorable conditions, such especially as stagnation, on the sea bottom; then, after the extinction of the destructive aërobic bacteria, it was long subjected to slow deoxidizing transformation by the anaërobic microbes. The work of the latter, which is most commonly evident through the generation of methane, may, unless arrested by complete elimination of the oxygen or by the production of toxin as a result of their own processes, persist for unknown but variable periods in the buried matter, of which much at least becomes chemically transformed under their influence.

Effective arguments for the prominent place taken by low plant orders in the ingredient matter of the mother rocks of petroleum are found in the microscopical examination of cannels, bogheads, oil shales, etcetera, which show that the organic deposits composed most completely of waxy spores, resins, fatty products, gelatinous algæ, and other associated organisms and their decomposition products will, when distilled, yield petroleums nearest typical and of higher ranks. This fact, which was demonstrated by Renault[6] and C. E. Bertrand,[7] and given practical interpretation by Potonié,[8] seems now to have won Engler,[9] among others. It may be noted that the rich oil shales of the Green River Eocene formation in the Uinta Basin of Colorado and Utah were found by the late C. A. Davis, who was studying them, to consist largely of spores, algæ, fungi, etcetera, mingled with the debris of other vegetable and animal types.

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[2] Bull. Soc. Imp. Nat. Moscow, vol. 3, 1890, p. 720.

[3] Rept. Brit. Assoc., 1891, p. 639; Chem. News, vol. 64, 1891, p. 191.

[4] Jour. Russ. Phys.-Chem. Soc., vol. 46, 1914, p. 1428.

[5] Econ. Geology, vol. 11, no. 6, 1916, p. 513.

The organic muds destined to form the mother rocks of petroleum were deposited in both saline and fresh waters; but while it is probable that certain types or certain characters of the oils were predetermined by the characters of the organic debris and the conditions of its deposition, including the duration of the anaërobic action, the special office attributed by some chemists, including Ochsenius, to the presence of salt in the generation of petroleum remains to be demonstrated. Even as a preservative tending to retard the decay of the organic detritus, as suggested by Zaloziecki,[10] its value is doubtful, for marine bacteria are as numerous and as efficient as those in fresh water, and it is well known that the destruction of animal matter in the ocean is not less rapid and complete than in lakes and ponds. In fact, it appears generally to be more complete. The sulphur in the Trenton and other marine limestone oils was probably yielded by the decomposition of marine animal organisms, only to be gathered again in the organic mud through the action of the sulphur bacteria, which are more common in the salt water. From the marine deposits, which are thus rich in sulphur, the latter has probably been taken in greater amounts by the oils. However, in other cases, as has recently been pointed out by Mabery, and fully established by G. S. Rogers in the Coalinga region of California, the sulphur is carried as sulphates in downward percolating waters, and liberated as hydrogen sulphide or free sulphur on reaching the first zone of the hydrocarbons, below which sulphates are absent. The tendency of oils to take up sulphur to their great deterioration has been strongly emphasized by Mabery.[11] The disappearance of the sulphates on reaching the hydrocarbon zone accounts also for their absence, as remarked by Thompson, in the underlying sands.

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[6] Micro-organismes des Combustibles Fossiles. Comptes Rendus, vol. 117, 1893, p. 593.

[7] Comptes Rendus Congr. Geol. Internat., 1900, p. 458.

[8] Entstehung d. Steinkohle, 5th ed., 1910, p. 95.

[9] Engler and Höfer, Das Erdöl, vol. 2, 1909, p. 59.

[10] Chem.-Zeit., vol. 15, 1891, p. 1203.

[11] Econ. Geology, vol. 11, no. 6, 1916, p. 526.

Distillation versus Bacterial Origin

However, as to the actual mode of origin of oil from plant and animal matter, there are, besides many minor differences of opinion touching one point or another, two divergent views of primary rank. The first view, with which all are familiar, is that supported by Newberry and Orton, but really centuries old, that petroleum is generated by natural earth processes more or less similar in effect to the distillation, under geothermal and dynamic influences, of the organic matter buried in the sediments. The other view is that the oil is generated through the action of anaërobic bacteria working in the putrifying debris as it is buried in the muds—at the time of or very soon after deposition of the organic debris.

The importance of microbes, particularly anaërobic bacteria, in the transformation of the organic compounds in the debris as it accumulates and becomes buried in the strata was clearly demonstrated with almost marvelous microscopical technique by Renault and Bertrand. This work of the micro-organisms affects *both* the accumulating debris, composed mainly of vascular plants and destined to form coals, and that composing the mother debris of petroleum, whether this debris be scattered in the muds of future shales, impure limestones, etcetera, or accumulated in relative purity to form future cannels and bogheads. This initial putrefaction process, the bacterial decomposition of the organic debris, I have for emphasis distinguished as the *biochemical* process, or the *biochemical stage,* in contradistinction to those chemical changes which are later induced in the buried organic deposits through dynamic or other influences of purely geologic origin, and which are, on the other hand, dynamochemical, or, to use a better word, *geochemical.* According to my view, the activity of the bacteria probably ceases before the organic deposits are buried to a great depth or have been subjected to any considerable dehydration, lithification, and progressive devolatilization. But it was Renault's belief that in the case of coals the rank of the coal, such as lignite, bituminous, or anthracite, was dependent solely on the kinds and the duration of the microbian action.

I am not aware that Renault ever applied his theory specifically to petroleum, though such an application is suggested in his discussions. The formal elaboration of the biochemical hypothesis of the origin of petroleum, making the oil a direct product of the putrefaction of the organic debris, seems to rest mainly on the observations noted by Sickenburger,[12] Redwood,[13] and A. B. Thompson,[14] which include the occurrence of oil in the scum of small bays of the Red Sea region and oil globules in the putrefaction muds and slimes of the salt marshes of Sardinia and on the shores of the sound near Lund, Sweden. Definite attribution of the oil to bacterial action seems first to have been made by Marrey in 1903.[15] In the discussion of the Burma oils, Murray Stuart,[16] whose conclusions are followed by A. B. Thompson and Marcel Daly,[17] concludes that the oil generated in the decaying organic matter is carried or held down in very small globules by particles of clay and detritus, and so is buried in the muds until, presumably in a later period, compression should force the oil, gas, and water into strata favorable for storage and gravitational segregation.

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[12] Chem.-Zeit., vol. 15, 1891, p. 1582.

[13] Petroleum, 3d ed., vol. 1, pp. 132-148.

[14] Oil-field development, 1916, p. 270.

It will be seen that, according to this theory, petroleum originates at first hand in the decaying organic debris before the organic muds, etcetera, have been deeply buried or subjected to geodynamic alteration. How, then, is to be explained the conversion of this primary oil, which no one has shown to be a typical petroleum, or even closely comparable to the oils known in any region, into the various grades of petroleum found in different areas? Marcel Daly[18] proposes to explain it by chemical transformation of the buried oils themselves under the influence of pressure, with little increase of temperature, at times of diastrophic movement, the importance of the time factor being emphasized. Thus, so far as it concerns the transformation of the oil under dynamic influences to successively higher ranks, the interpretation given by Daly agrees with that followed by Mabery and others, including myself. A. B. Thompson, on the other hand, noting that in all probability colloidal enzymes are produced in the course of the bacterial action, urges that these may play an important part as *catalysts,* not only in determining the characters of the oils, but in stimulating chemical reactions at times of increase in pressure or temperature. He says:[19]

> ". . . It may well be that the colloidal enzymes resulting from anaërobic bacterial action are buried with the organic material they are acting upon, and there continue their action, for there is no obvious reason why, as catalysts merely, they should cease to perform their functions so long as sufficient unstable organic material remains, and they themselves are not destroyed by heat, or inhibited by the products of their action. . . .
>
> "Thus the actual hydrocarbon product would seem to depend upon (*a*) the nature of the primary organic matter; (*b*) the particular character of the catalytic enzymes; (*c*) the temperature and pressure reached before complete conversion; and (*d*), finally, the adjustment of constitution and proportions

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[15] Bull. Geol. Survey Ohio (4), vol. 1, 1903, p. 313.

[16] Rec. Geol. Survey India, vol. 40, 1910, p. 320.

[17] Trans. Am. Inst. Min. Eng., July, 1916, p. 1152.

[18] Trans. Am. Inst. Min. Eng., July, 1916.

[19] Oil-field development, 1916, pp. 271-272.

of the various hydrocarbons would depend upon both the actual pressure and the amount of uncondensed gas. Increase of temperature probably only acted as an accelerator of the catalytic action."

It may not be out of place to add at this point that most petroleum theorists now assume that under certain circumstances, generally not specified, filtration as proposed by David T. Day has operated, locally at least, in changing the character of the crude oils while migrating.

Influence of Chemical Processes

In a previous paper[20] I have shown that between coal, oil shales, and petroleum there is much in common as to origin. Whether the ingredient organic matter, be it plant or animal, will be in part transformed to coal of the ordinary type, to cannel, to oil shale, to the organic residues in so-called bituminous shales and carbonaceous shales, or to petroleum and natural gas, is dependent upon the composition of the ingredient organic debris, the conditions of its accumulation or deposition, and the extent of the microbian action.[21] Further, this question is determined before the close of the initial or biochemical stage of the transformation of the organic matter. On the other hand, the alteration of peat (biochemical stage) to coals of successive ranks, such as lignite, sub-bituminous, bituminous, etcetera, is, I hold, the result of geochemical processes induced under dynamic influences, especially thrust pressures with their attendant temperatures. The greatest changes attend the greatest and most prolonged dynamo-thermal activity. This alteration of the organic detritus is progressive, and is marked not only by physical changes in the detrital deposit, but in particular by the gradual elimination of its volatile matter, including volatile hydrocarbons; and this takes place in the cannels, oil shales, and bituminous shales, as well as in the coals associated in the same formations or groups of formations and in the same areas. Also it is found that up to the point of too great devolatilization of the oil shales or cannels, the progressively more altered shales, when distilled, yield the oils with the greatest amount of light hydrocarbons. These distillates are, in effect, crude petroleums, though they do not exist as such in the organic debris or residues which gradually become carbonized as coal or as disseminated particles in shale, sandstone, etcetera.

Noting the gradual elimination of the volatile hydrocarbons—the so-called volatile matter—from the oil shale simultaneously with the devolatilization of the associated coals in the course of the progressive regional alteration of the organic deposits, I have called attention to several other points which seem to indicate a mutual relationship between coal and petroleum in the second or *geochemical* stage of development, and that both react to the same geophysical influences, as follows: (1) That in regions where the coals and other carbonaceous debris in the strata are of the rank of brown lignites, the oils in the same or closely associated geological formations are also of low rank, averaging 20° to 26° Baumé; (2) that where the organic debris (coals, etcetera) has advanced to the subbituminous rank, the oils of the same or of nearly contemporaneous underlying formations are of higher rank, averaging 28° to 35°; (3) that when the deposits of organic debris have been regionally transformed (by elimination of volatile matter) until they have reached the bituminous rank, the oils have in general attained a rank of 35° or more, the highest grade of petroleum being found in the areas where the regional alteration of the organic debris has progressed farthest; *except* (4) that in those regions where the organic debris, whether it be represented by beds of coals, by bogheads, or by carbonaceous matter in shales, has passed the point corresponding to a content of 65 per cent of fixed carbon, pure coal basis, the oils which may formerly have been present in the same or in the underlying formations have mostly disappeared; and (5) that wherever the devolatilization of the coals, etcetera—that is, the solid residues in the strata—has progressed so far that they have a fixed carbon content of 70 per cent or more, *oils,* if present, will be "freak" oils, and in pockets or amounts too small to be of commercial importance, though gas pools may persist. I know of no commercial oil pools in the world that are found in or beneath formations in which the regional carbonization of the organic debris has passed 75 per cent fixed carbon, pure coal basis; in fact, I have not yet been able to learn of an oil pool in or beneath a formation in which the fixed carbon percentage of the organic debris exceeds 70, and it is most improbable that oil pools exist under such conditions.

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[20] Jour. Wash. Acad., vol. 5, no. 6, 1915, p. 189.

[21] White and Thiessen: Origin of coal. Bureau of Mines Bull. 38, 1913.

It will at once be seen that these conditions seem to define a law restricting the distribution of productive oil pools, and to afford a basis on which to eliminate many areas of great extent in which fruitless and costly exploration by the drill is now going forward.

Effects of Progressive Regional Alteration

But what is the genetic significance of all this? It is certain that the progressive regional alteration of the rocks, including coals, etcetera, is attended in general by a corresponding progressive advancement of the oils to the point where they have a maximum content of light hydrocarbons, and that beyond this point they seem to have been in some way eliminated or distilled off. Is not this general advancement of the petroleums induced by the same geologic causes under which the organic detritus remaining *in situ* as coals, etcetera, has, in effect, been progressively fractioned, especially during periods of rock compression, with losses of methane and other light hydrocarbons, so that the solid residues are undergoing carbonization? Whether the oils were generated in the biochemical process, or, later, in the geochemical process, have they not also been fractioned from time to time—that is, practically redistilled under dynamo-thermic influences, the liquid distillates becoming successively lighter and the residues more fully solidified? And have not the volatile hydrocarbon stores deeply buried in the strata been perhaps replenished or possibly replaced in times of diastropic stress by additions derived from the reduction, essentially a distillation, of the mother rocks? That there was some heat resulting, firstly, from the rock compression, and, secondly, from the chemical reactions themselves, all are agreed, though most of us insist that the temperatures were comparatively low.[22] Washburne,[23] on the other hand, pointing out the exothermic nature of petroleum, insists that considerable heat was essential to the reactions.

Richardson's Hypothesis

An undeveloped hypothesis, full of interest and suggestion, that has been presented by Clifford Richardson,[24] is that the origin of all forms of petroleum is to be viewed with reference to the phenomena of surfaces and films, as demonstrated by recent developments in colloidal chemistry, and that petroleums of all sorts are to be attributed to surface action between a natural gas and the "sands."

Conclusion

He who would solve the problems of physical chemistry involved in the origin of petroleum must studiously take account of all the physical factors obtaining in the mother rock and in the oil sand, including among his factors not only temperature and pressure, but the size of the globules in the capillaries and pores, and the physical and chemical relations of the oil, gas, and moisture as they are found disseminated in all the rocks. In this connection it may not be out of place to note that as the conditions of nature seem more fully to be imitated in the refinery, the larger production of the lighter hydrocarbons is gained, with wider separation between them, and the residues are more fully solidified.

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[22] This general point of view is tersely and succinctly summarized by Johnson: See R. H. Johnson and L. G. Huntley, Principles of oil and gas production, 1916, p. 24.

[23] Trans. Am. Inst. Min. Eng., 1914.

[24] Jour. Indus. and Eng. Chem., vol. 8, no. 1, 1916, p. 4.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 28, PP. 735-744 DECEMBER 4, 1917

PROBLEMS OF THE INTERPRETATION OF SEDIMENTARY ROCKS[1]

BY A. W. GRABAU

(Presented before the Society December 29, 1916)

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INTRODUCTION

In the development of geological thought it was but natural that attention should at first be largely directed to dynamic phenomena and agents and to the structures resulting from their activity, and that geologists should be chiefly occupied with the elucidation of these structures. True, the stratified rocks of the earth's crust have called forth speculation from the very beginning, but mainly on account of their fossil contents. Questions of classification and correlation of the formations based on superposition and on the inclosed organic remains have to a large extent engrossed the attention of the stratigrapher since the days of Lehman and William Smith. That the characters of the rocks themselves could be of any significance seems to have been realized by few, and these few considered such characters generally only from a special, often only a mineralogical, viewpoint. More recently the phenomena of alteration or

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[1] The first of a series of papers composing a "Symposium on the Interpretation of Sedimentary Rocks."

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metamorphism of sediments have claimed attention, and indeed to some students all rocks are metamorphic rocks and have no other significance. That metamorphism of some kind or other affects all rocks from the beginning, that indeed the material of which many sediments are made is the product of metamorphism by disintegration of older rocks, is perfectly true. This and the changes which rocks undergo as the result of normal maturation have long been recognized by the student of sediments as the phenomena of diagenism. But such phenomena, while not neglected—indeed often carefully considered—are of secondary importance when compared with the more fundamental problems of origin, which have now begun to receive the notice they deserve. Again, where formerly the secondary structures induced by disturbances and readjustments attracted geological students, today the original structures of rocks, or those produced in the process of rock-making, have begun to claim chief consideration.

THE EARLY AND MORE RECENT INVESTIGATORS OF SEDIMENTARIES

In this return to the study of the rocks themselves from the consideration which their distribution and age relations had previously claimed, it was natural that attention should be largely centered on the crystalline rocks, which, from their varied mineral composition and frequent complexity of structure, offered an attractive field once the way was shown by the invention made by William Nichol and by the genius of Henry Clifton Sorby. Sedimentary rocks, from their apparent simplicity and relative uniformity, did not at first attract the new school of petrographers. The responsibility for this is perhaps to be laid at the door of the two great continental masters in this field, Ferdinand Zirkel and H. Rosenbusch; but it should be noted that Sorby—the father of modern petrography—was not unheedful of the problems offered by the sediments, and in 1889, and again in his last work, published after his death, he has given us a masterly treatise on certain phases connected with the composition and structural characters of sediments.

No one, I think, will dispute my statement that the science of the petrogenesis of sediments naturally had its beginning in the work of Prof. Dr. Johannes Walther, who, while Haeckel Professor of Geology and Paleontology at Jena, issued in 1893-1894 his masterly "Einleitung in die Geologie als Historische Wissenschaft." We are especially concerned with the volume on "Lithogenesis der Gegenwart," which for the first time brought together the scattered observations and deductions on the nature and origin of modern sediments which had previously appeared in geological and oceanographic literature, and to which Walther added extensively from his store of observations in all parts of the world.

Although this work tended to focus attention on the several types of modern sediments and on the conditions under which they were forming, and thus placed a distinct milestone along the path originally blazed by Lyell, Walther's name will probably always be most fully identified with the study of modern terrestrial sediments, for here he made most extensive contributions. Though many pioneers preceded him, their work was mainly that of gathering the blocks which were incorporated by Walther in the foundation of the structure on which we are building today. Attention of the geological world was directed to this previously little-known field by the appearance in 1891 of Walther's epoch-making studies on "Die Denudation in der Wüste und ihre geologische Bedeutung," and was firmly riveted when, at the opening of the new century, appeared the first edition of "Das Gesetz der Wüstenbildung." Henceforth the name of Johannes Walther was closely linked with the subject of desert studies in the minds of geologists, so much so that his continental brothers of the hammer came facetiously to refer to him as "den Wüsten Walther," a designation susceptible of two quite distinct interpretations.

While thus giving to Walther the credit of inaugurating, though not originating, a new line of investigation, we must not neglect to mention others who contributed to the development of this new field. Probably foremost among them should be noted the Russian geologist Sokolow, whose work on the structure of sand-dunes was made available by the appearance of the German translation in 1894; nor must we neglect the contributions of the physiographers who so frequently have pointed the way which the student of lithogenesis should follow. Penck's "Morphologie der Erdoberfläche," which appeared in 1894, can not be ignored by the students of sediments any more than can Passarge's ponderous work on the Kalahari, which appeared ten years later (1904). The importance of Suess's work is too well understood by the student of lithogenesis to require further comment. In our own country, the writings and teachings of W. M. Davis have formed perhaps the most valuable training for the rising school of American lithogenesists, and probably most of the American workers in this field, and not a few foreign ones as well, acknowledge their faith in the soundness of his principles.

While speaking of the works on modern continental sediments which appeared in the closing decade of the last century, we must not forget the studies of Johan A. Udden on the mechanical composition of wind deposits, which appeared in 1898, and which were followed by other papers of similar significance. The many important observations contained in the broader studies of Palgrave (1865), Von Richthofen (1877), Prjevalsky (1883), Pumpelly (1908), Huntington, and others are all familiar to the modern student of continental sedimentation.

While Walther and the physiographers were thus placing the study of lithogenesis of the continental deposits on a firm basis, Bailey Willis, in this country, and Thoulet, in France, as well as Walther himself, were directing our attention in greater detail to the sediments forming on the bottom of the sea and along its shores. This field had, however, been cultivated for some time by students of modern phenomena, and one need but mention the names of Delesse, Daubré, and Rutot in France; of Edward Forbes, Charles Darwin, J. Y. Buchanan, and W. J. Sollas in England; of Forchhammer, Gümbel, and G. R. Credner in Germany, and of Pourtales and Alexander Agassiz in America, to call attention to some of the chief workers in this field during the middle and closing decades of the nineteenth century. Thoulet's reports to the Paris Academy of Science began to appear with the opening of the new century, but Bailey Willis's studies were contemporaneous with those of Walther. The masterly report of Sollas on the Estuary of the Severn appeared in 1883, and that of R. H. Worth on the Bottom Deposits of the English Channel in 1899. That Englishmen and Scotsmen should come to pay particular attention to marine deposits and phenomena is but natural, from their position in the embrace of the ocean, and so it is no wonder that many of our seacoast as well as deep-sea investigations during the closing years of the last and the opening of the present century were made by natives of the British Isles. This was so in the day of Lyell and Edward Forbes, and it culminated in the volume on deep-sea deposits by Murray and Renard in 1891, and the subsequent works on deep-sea sediments which appeared from the pen of Murray and his collaborators. That many important facts were brought to light by the deep-sea expeditions under Agassiz is well known, but these have not yet resulted in a comprehensive treatise on marine deposits. Here, too, we must mention the work carried on by the Prince of Monaco and his staff, and that of the Kommission zur Untersuchung der deutschen Meere. Nor must we forget the important oceanographic studies of Krümmel, which led to the writing of the indispensable "Handbook of Oceanography," the first volume of which appeared in 1907; and finally we must recount the important investigations made by Walther on the "Sediments of the Bay of Naples." A disciple of these two masters, Carl André, is now actively carrying on the study of marine sediments, and has already produced results of great importance to the stratigrapher.

It would go beyond the scope of this paper to mention all who have contributed to the advancement of our knowledge of marine sediments, but a few additional ones may be listed. Thus among contemporary English writers we should mention Cornish, Wheeler, Blake, and Joly; among the the French, Collet and Cayeux; among the Germans, Philippi, Schott, and Supan, and among the Russians, N. Andrussow. The American workers in this field we all know, and some of them are to follow me in this symposium.

Chemical Deposits

The study of modern chemical deposits has enlisted the attention of many workers, both in this country and abroad. It would not be easy to give an adequate analysis of the works of importance to the lithogenesist in the short time allotted, but a few of the more prominent workers may be noted. Perhaps we all agree that the studies of Usiglio, in 1849, on the precipitation of salts from evaporating sea-water laid the basis for most of our subsequent work on marine salts, and that the publications of Ochsenius on rock-salt deposits and the mother liquor, in 1877, 1878, and 1888, are of fundamental significance. The more recent, detailed investigations of Van't Hoff and his associates, which belong to the contributions of the present century, are too well known to need further comment. Many names might be cited of those who have added to our knowledge of modern chemical sediments, both in the sea and on the continent, but reference can be made only to a few. From among the many Germans who have attacked problems in this field we may note E. Erdmann, Hochstätter, Lachmann, Linck, and Philippi. English contributors include Robert Irvine and his associates on the work of the *Challenger* expedition; the French workers, Paul Reynard and others, and the Americans, F. W. Clarke, I. C. Russell, J. C. Branner, T. Sterry Hunt, E. W. Skeats, and many others.

Organic Deposits

Recent organic deposits, both on sea and land, have been treated perhaps most extensively by Americans, though Englishmen, Germans, and to some extent French investigators have furnished important contributions. The coral-reef studies of Darwin, Dana, and Davis, and those of Agassiz, Murray, and Vaughan, are all well known. The Funafuti report, under Sollas, and the studies of deep-water organic deposits by Murray and others of the Challenger expedition, and those of Pourtales and Agassiz in America, and by Krümmel and other Europeans, the studies of lime secretion and precipitation through the agency of algæ by Marshall Howe and Rothpletz, and through bacteria by Drew, Kellermann, and Vaughan, indicate the lines of work which have been pursued. Finally, the detailed study of terrestrial deposits of vegetal origin, such as those of C. A. Davis and David White in this country, of Gunnar Samuelson in Scotland and Scandinavia, and of Ramann on the German Moors, are of fundamental significance. The masterly treatise of Potonié, "Die Entstehung der Stein-Kohle und der Kaustobiolithe überhaupt," which has already passed its fifth edition, furnishes the standard European reference work, as does the equally authoritative summary of our present knowledge of coals and coal formations by our own J. J. Stevenson for the English-speaking world. Finally, we can not omit to mention the promising investigations on the origin of coals recently begun by the botanist Jeffrey in this country.

THE OLDER SEDIMENTARIES

So far I have been considering mainly the investigators among recent sediments. The application of the knowledge gained from these to the interpretation of older deposits has been of slower development. From the very first, students of sediments have been in the main marinists, though when the organic evidence pointed unmistakably to the presence of fresh waters they resorted to a lacustrian variant. Even today the interpretation of sediments as of other than marine or lacustrine origin meets with a good deal of skepticism in some circles, and the fluviatilists are not in much favor, especially when they intrude upon territory hitherto preempted by the marinists. When, in addition, they have the temerity to carry an entire group of organisms along with the sediments from the sea into the rivers, they needs must possess the courage of their convictions, for they can not look to much support. Fortunately, however, American geologists are the most tolerant of men, and even the most startling ideas get a hearing if they are supported by facts and are the result of logical reasoning.

CHANGE OF FACIES

Although it was always recognized by students of modern marine sediments that the facies of the deposit changes continually, this principle was rarely applied to the extent that it might have been in the interpretation of the older rocks. This was especially the case where two facies progressively replace one another. We all recall the Catskill-Chemung discussions of two decades ago, and I remember well when the president of our Society, Dr. Clarke, announced at the Rochester meeting the discovery of the eastward replacement of the Onondaga limestone by the Marcellus shale, an announcement which to me opened broad vistas of correlational possibilities, down some of which I have since adventured. That such replacements of rock facies, with a corresponding replacement of adapted organic types, rather than a succession of stratigraphic breaks or hiatuses, explains many of the puzzling phenomena in our stratigraphic columns is the growing conviction of students who approach the science through the avenue of lithogenesis. The correlation of rock facies is, of course, closely bound up with the question of the origin of the sediments, and for this reason the determination of the source and the manner of transportation of the material becomes a vital question. On this account mechanical analysis of older deposits, based on the methods and principles developed in the modern sediments, must take a prominent place in our discussion, and it is a matter of congratulation that this problem, so auspiciously inaugurated in this country by Goldman, is being vigorously attacked by American geologists.

It may perhaps be acknowledged that in general we need be at no loss for criteria by which to interpret a normal marine deposit of the littoral zone, and that, too, we know by what tokens a certain rock is excluded from the category of deep-sea sediments. And yet we can not be so certain that a foraminiferal rock like the white chalk or a pteropod ooze like the Genundewa limestone, which show some of the most pronounced characteristics of deep-sea oozes, are not after all shallow-water deposits. We know too little of seashore sediments and the permanency or evanescence of the structural features impressed upon them, and their chance of preservation, to apply these criteria with certainty to the interpretation of older sediments. Who can say what type of cross-bedding, if any, is characteristic of the seashore? And who has established beyond cavil the conditions under which such structures are formed, and, above all, preserved? Of ripple-marks and beach-cusps we feel more certain, and yet who can say what are the conditions necessary for their preservation and what the conditions inimical to it? And when we try to recognize ancient estuarine and lagoon deposits, where shall we find the infallible characters by which we may interpret these? And does this not apply to deltas as well, though here, perhaps, we stand on surer ground? It is evident that much work along seashores is still necessary before we can hope to do more than approximate in our attempts at interpretation.

THE OLDER CONTINENTAL DEPOSITS

The case is less desperate when we adventure upon the continent, for here we have already a wealth of data gathered with especial intent to serve as a basis for interpretation, though it must be confessed that very much remains to be accomplished. And since Walther and the physiographers have shown us the way, a fair amount of interpretational work of the older continental deposits has been attempted. Strange to say, some of the earliest contributions along this line were made by geologists from the British Isles, that stronghold of marine conservatism. That Medlicott and Blanford should, in the late '70's, interpret the Siwalik formation of India as a sub-recent fluviatile example, is readily enough understood, for they had before them the Indo-Gangetic plain in process of formation, the deposits of which were identical with that of the upturned Tertiary of the sub-Himalayan region. But that British rocks should by Britishers be interpreted as continental formations is more remarkable. Perhaps as canny Scotsmen, Mackie and Goodchild were more likely to dissent from the prevailing English view, just as Hugh Miller was perhaps the first to suggest the fresh-water origin of the Old Red Sandstone, in his day a heresy which was duly quashed by the imperious Murchison. Mackie and Goodchild twenty years ago gave evidence pointing to the fluviatile and æolian origin of the Old Red Sandstone and the existence of desert conditions in Britain, and Lomas followed ten years later with a discussion of desert conditions during the formation of the British Trias. During Walther's visit to Scotland he apparently convinced Peach and Horne of the subaerial origin of the Old Red and Torridon sandstones, and so brought into the camp of the continentalists two men, than whom none have a more intimate knowledge of, or speak with greater authority on, the older rocks of Scotland.

That Walther should find many disciples in Germany was, of course, to be expected, though those who know the temper of the German scientists will not be surprised to find that he was perhaps more violently opposed in his own land than elsewhere. But today the younger geologists of Germany ardently pursue "Sediment-Petrographie," and in Germany as well as in France lithogenesis of sediments is a live study.

In America the recognition of older continental deposits is of more recent date. W. D. Matthew, in 1899, discussed the possible æolian origin of the White River beds, and Davis, in 1900, interpreted the Rocky Mountain Tertiary deposits as fluviatile in origin. Penck had previously made suggestions along those same lines from studies carried on during a visit to western America. Since then most of our sediments have been subjected to a certain extent to lithogenetic analysis, though we are far from being agreed on all the interpretations which have been offered.

MICROSCOPIC STUDY OF THE SEDIMENTARIES

The microscopic study of our sediments has hardly begun, nor have chemical and physical analyses adequate to the requirements of the problem been made of more than a few of our clastics. Neither is the stratigraphic relationship of our chemical deposits better known, while our ancient reef rocks and other organic deposits have received hardly more than passing notice, though this does not apply to the coals and other related deposits. Perhaps if we stratigraphers insisted on a more refined classification of our sediments, instead of being satisfied with conglomerates, sandstones, shales, limestones, and some minor types, we would make more rapid progress; for it is my belief that precision in classification leads to precision in thought, and so is of vast value as a mental discipline. It might not be amiss to insist that a firm foundation in the classification of our rocks is a needful preliminary to the building of a permanent superstructure, and to urge that we get together and follow the lead of the pyro-petrographers.

THE FUTURE OF THE SCIENCE OF LITHOGENESIS

In the future, the study of lithogenesis must go hand in hand with the study of paleogeography. Neither science can progress without the other, and each is dependent on the other to a degree often too little recognized. For its proper prosecution, the study of the genesis of a given sedimentary rock requires not only the chemical, microscopic, lithologic, and paleontological investigation of the mass itself, but its field relations can not be neglected. Moreover, it must be obvious that the history of a deposit can seldom be fully ascertained from the study of a limited area, or even of the entire area of its occurrence. The characteristics and distributions of the formations representing it elsewhere must be taken more account of in the future than they have been in the past. As an illustration, there may be cited the genesis of the Siluric salts of North America, which can only be understood when the Siluric formations of the greater part of the North American continent are understood. In like manner, the lithogenesis of the Mauch Chunk shale and that of the Pottsville conglomerate can only be fully understood when we have a knowledge of the locations of the mountains, lowlands, and seas of the respective periods, and this requires the study of the Mississippic and Carbonic formations of a considerable portion of North America.

Above all, we must broaden our knowledge of the physical conditions under which sedimentary deposits are formed today, and we must replace the inadequate and often too superficial descriptions, given us by the geographers and travelers, by the more detailed and exact observations which only the trained geologist can make.

"Twenty years ago," Walther writes,[2] "I was constantly told: 'What you are doing is not geology.'" He paid the penalty of leaving the path where orthodoxy was wont to travel. Today the science of lithogenesis founded by Walther is coming into its own, and this symposium, conceived of the wisdom of our president, gives promise that in this field, too, we in America may hope to march in the front ranks of those whose business it is to advance the boundaries of human knowledge.

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[2] Private communication.

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RHYTHMS AND THE MEASUREMENTS OF GEOLOGIC TIME[1]

BY JOSEPH BARRELL

(Presented before the Society December 29, 1916)

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[1] The second of a series of papers composing a "Symposium on the Interpretation of Sedimentary Rocks." It was presented at the Albany meeting, December 29, 1916, under the title "The Significance of Sedimentary Rhythms." It formed the first and second parts of a paper entitled "The Measurements of Geologic Time," delivered as two addresses in the University of Illinois Public Science Lectures on January 16 and 18, 1912, at Urbana, Illinois. The author feeling that condensation would diminish greatly the value of the paper, the Publication Committee of the Society consented to publish it in full under the title given above.

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Introduction and Summary

Nature vibrates with rhythms, climatic and diastrophic, those finding stratigraphic expression ranging in period from the rapid oscillation of surface waters, recorded in ripple-mark, to those long-deferred stirrings of the deep imprisoned titans which have divided earth history into periods and eras. The flight of time is measured by the weaving of composite rhythms—day and night, calm and storm, summer and winter, birth and death—such as these are sensed in the brief life of man. But the career of the earth recedes into a remoteness against which these lesser cycles are as unavailing for the measurement of that abyss of time as would be for human history the beating of an insect's wing. We must seek out, then, the nature of those longer rhythms whose very existence was unknown until man by the light of science sought to understand the earth. The larger of these must be measured in terms of the smaller, and the smaller must be measured in terms of years. Sedimentation is controlled by them, and the stratigraphic series constitutes a record, written on tablets of stone, of these lesser and greater waves of change which have pulsed through geologic time.

The doctrine of uniformitarianism has ignored the presence of age-long rhythms, and where they were obtrusive has sought to smooth them out; but in so doing it has minimized the differences between the present and the past, and the constant variations within that past. This doctrine should be looked on only as supplying a beginning for investigation; the establishment of a datum plane against which may be sought out and measured the amplitudes of oscillations of all factors which have found a direct or indirect record in the crust. This, of course, is not easy, since the causes are often obscure and the degree of variation in period and in amplitude of each factor must be determined and tested by comparison with unrelated factors.

Although, in a later part of this article, a review is given of the evidence furnished by radioactivity, the viewpoint of the paper is geological, the first three parts consisting in a study of the variations to which the rates of geologic processes have been subject. In the assemblage of material and the manner in which the subject is treated here, it is essentially new, although Blytt, Gilbert, F. B. Taylor, E. Huntington, and others have dwelt on one aspect or another of this subject.

In Part I of the paper it is pointed out that erosion is essentially a pulsatory process, as Davis has made most clear and the students of physiography are now well aware. A single rhythm is the erosion cycle; and small partial cycles are superimposed on larger. How much has this pulsatory nature led to variations in the rate of regional and continental denudation in the past, and what is its significance in regard to the sedimentary measures of geologic time? The answer is reached from several points of view in this article that, because of the present great elevation of the continents, because of the magnitude of recent orogenic movements, and because of the pulsatory nature of the Pliocene-Pleistocene uplifts, forming an accelerated series, a concurrence of factors has taken place each of which makes for a high rate of denudation. Their combination must give a rate very much greater than the mean for geologic time.

Passing in Part II to the next step in the argument: in all stratigraphic measures of geologic time, so far as the writer is aware, the rate of deposition of a sedimentary series has been previously regarded as dependent on the type of sediment, whether sandstone, shale, or limestone, combined with the present rate of supply of such sediment to regions of deposition. Here is developed an opposite view: that the deposition of nearly all sediments occurs just below the local baselevel, represented by wave base or river flood level, and is dependent on upward oscillations of baselevel or downward oscillations of the bottom, either of which makes room for sediments below baselevel. According to this control, the rate of vertical thickening is something less than the rate of supply, and the balance is carried farther by the agents of transportation. The storage of the final excess, except for locally deep water on the lands, is on the abyssal slopes of the continental platforms, constituting deposits lost to observation, since it is a region which has been seldom uplifted and exposed by erosion.

Thus, sedimentation, as well as erosion, is dependent for its rhythmic rejuvenation on changes in baselevel, emergence above baselevel determining erosion, submergence below baselevel giving sedimentation, either of continental or marine deposits. This control of sedimentation by baselevel may be summed up in three principles:

First, the rate of sedimentation is determined usually not by the rate of supply of sediment, but by the rate of the discontinuous depression of the surface of deposition.

Second, subsidence of the sedimentary floor is not initiated by the load of sediment, for depression must precede. When a movement of subsidence has begun, however, the weight of sediment will act in the same direction, but it is a secondary cause. Sedimentation, then, is the effect of depression to a greater degree than it is the cause.

Third, the deposition of a series of beds where the material is carried along the bottom by stirring of currents or oscillations of waves is ordinarily not a continuous process, even during a stage of crustal depression, but represents an irregularly rhythmic alternation of fill and scour with a balance in favor of the fill. There are minor time blanks, consequently, in what appears to be a continuous succession of beds, and larger and larger intervals separate the larger and larger divisions of a series.

Numerous breaks are now known to exist in which the beds above and below lie parallel, and, except for some change in fauna or flora, give little or no indication of the great lapse of time which occurred between their deposition. Such breaks are known as disconformities. The present argument enlarges on this conception, holding that the breaks of smaller time interval are still more numerous and may add up to equally large measures of time unrecorded by sedimentation. Such breaks have generally been too brief to give a clue by means of a faunal or floral change, but must be recognized through the physical features of the beds, often most readily because of a sudden change at the break in the character of the rhythms expressed in sedimentation. It is proposed to recognize the aggregate importance of such minor breaks by giving them a special name. The name selected is diastem. Diastems range of all values from seasonal cessations of sedimentation to those which approach geologic epochs in duration.

Combining the indications regarding the present high rate of denudation with the evidence of the halting and discontinuous nature of past deposition, it is seen that geologic time is certainly much longer—perhaps ten or fifteen times longer—than the estimates based on strictly uniformitarian interpretation.

Judged in the light of these arguments, 250,000,000 years may be regarded as a moderate estimate, from the geologic data, of the lapse of time since the beginning of the Paleozoic. The indications from radioactivity are in fact that it is more than twice as long as even this figure of 250,000,000 years, and the geologic evidence is seemingly not in conflict. An estimate of 250,000,000 is a return to the order of magnitude of the guesses made by Lyell and Darwin before Sir William Thomson, later Lord Kelvin, began to cut down to a small part of this estimate the capital of years which could be drawn on by geologists from the bank of time. Not recognizing the importance of the principles just stated, and feeling the need, so far as possible, of meeting the demands of the physicists, geologists found it easy to make lower estimates, though difficulty was found in compressing them to the later narrow limitations of 10,000,000 to 20,000,000 or 40,000,000 years for the age of the earth as set by Tait, Kelvin, Ritter, King, and others.

With the opening of the twentieth century the discovery of radioactivity disclosed, however, undreamed of stores of thermal energy. This discovery revealed with startling suddenness the unfounded nature of the assumptions, previously unquestioned, on which rested the restrictions that physicists had placed on geologists. Not only did physicists destroy the conclusions previously built by physicists, but, based on radioactivity, methods were found of measuring the life of uranium minerals and consequently of the rocks which envelop them. Instead of limiting earth history to less than 40,000,000 years, they now granted upwards of 1,500,000,000. Many geologists, adjusted to the previous limitations, shook their heads in sorrow and indignation at the new promulgations of this dictatorial hierarchy of exact scientists. In a way. this skepticism of geologists was a correct mental attitude. The exact formulas of a mathematical science often conceal the uncertain foundations of assumptions on which the reasoning rests and may give a false appearance of precise demonstration to highly erroneous results. No better illustration could be given than that of the case in point. This skepticism was incorrect, however, unless it led to a careful and unprejudiced reexamination of the postulates on which rested the geologic measurements of time.

Looking at the geological side of the problem from the standpoint of the control of sedimentation by baselevel, a subject which had at that time recently engaged the writer's attention, rather than by the present rate of denudation,[2] he stated in 1906 to Professor Boltwood, the first to seriously develop the evidences of age based on radioactive processes, that no real conflict appeared to exist between the geological facts and the new physical evidence. The conflict was only with one of the several possible interpretations of that evidence, though one which was generally accepted.

This article, as previously stated, is primarily an analysis of the geologic evidence, taking in especially the influence of the fundamental factor of composite rhythms, but it would be incomplete if it discussed only the interpretation of sedimentary processes in terms of rhythms. Such a discussion might fail to carry conviction of the great lengthening which it implies in the vista of geologic time, and at best would be qualitative rather than quantitative. Consequently, in Part III, a review is given of the methods of measurement based, first, on erosion and sedimentation; second, on chemical denudation and the sodium in the sea; and third, on the thermal gradient of the crust. In this review care is taken to examine the postulates which underlie these methods and which have resulted in current estimates of geologic time very much smaller than the estimates reached by the consideration of sedimentary rhythms and the measurements based on radioactive processes.

Another method is that of the detection of rhythms in parts of the sedimentary series, and the correlation of these rhythms with known climatic cycles. The use of the precession cycle has given very long estimates for these small pieces of geologic time. There are suggestions, however, derived from postglacial time, that the rhythm which is prominent is not so long as the precession cycle of 21,000 years, but is probably a rhythm in solar energy several thousand years in length. Such a conclusion comes into accord with the other lines of analysis of this paper, extending geologic time far beyond the generally accepted maximum limit of a hundred million years.

This is followed in Part IV by a presentation of the evidence from radioactivity, as based on the accumulation of helium and lead in radioactive minerals. Such a presentation seems all the more necessary, since no adequate treatment of that subject has been published in American geological literature. It is made easier at the present time by the publication in England in 1915 of an article by Professor Arthur Holmes,[3] an investigator who has done much work on this subject.

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[2] Joseph Barrell: Relative geological importance of continental, littoral, and marine sedimentation. Journal of Geology, vol. xiv, part 1, 1906, pp. 316-356.

Becker in 1908 published an article on the "Relations of Radioactivity to Cosmogony and Geology."[4] On pages 127 to 135 of this article is discussed the subject of "Radioactivity and the earth's age." Becker's argument and conclusions are strongly adverse to the value of the radioactive methods for determining age. This result is based in considerable part on the conflicting testimony derived from the radioactive minerals of the Llano district in Texas. In order to weigh these criticisms, the writer has examined the original data and finds that, instead of being opposed, they strongly support the hypothesis that the ratio of lead to uranium in uranium minerals, serves, when properly used, as an index of age. A hypothesis gains greatly in strength when what appeared to be conflicting evidence is resolved into supporting evidence. For this reason the facts for the Llano region are given in Part V in some detail.

Thus this article seeks to bind the geological and physical arguments into a unity—the geological data giving evidence of highly variable rate and imperfection of record, the physical evidence supporting the assumption of constant rate for radioactive processes and giving the magnitude of the framework into which the geological picture must be set. That framework is given in Part VI, the concluding part, as a new table of geologic time, and is of more generous proportions than geologists would have dared to assume from the data of their field alone; but it appears on testing from various points of view to have been logically constructed and gives room for a bolder and larger treatment of earth history than has been imagined to be held within the past. This table of geologic time is constructed by the dovetailing of two lines of evidence, as follows:

First, the thicknesses and character of the sediments give stratigraphic ratios of the lengths of the several periods. These, for reasons discussed, are subject to considerable uncertainty; yet, when derived with a knowledge of the variables involved, the ratios give some measure of the relative durations. Second, the quantities of helium and lead in radioactive minerals give minimum and maximum measurements of age. These ages are open to some uncertainty because of loss of helium or the presence of original lead, and the stratigraphic positions of the rocks holding the minerals are also in most cases not closely known. Nevertheless, the radioactive minerals give measures of absolute age which are of the right order of magnitude and in proper sequence, as shown by the geologic data.

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[3] Radioactivity and the measurement of geological time. Proc. of the Geologists' Association, vol. xxvi, part 5, 1915, pp. 289-309.

[4] Bull. Geol. Soc. Am., vol. 19, pp. 113-146.

The adjustment of these two lines of evidence serves as the basis for a table of geologic time stated in years. Such a table is comparable to the first crude measurements of the distances of the stars in space. The progress of research will continually refine the determinations and lead to a higher order of precision. On the present data Cenozoic time is determined as between 55,000,000 and 65,000,000 years long; the Mesozoic as covering between 135,000,000 and 180,000,000 years; Paleozoic time endured between 360,000,000 and 540,000,000 years. The summation of these minimum and maximum figures indicates that the beginning of the Cambrian was between 550,000,000 and 700,000,000 years ago. This may seem to be a wide latitude, but the ratio of the minimum to the maximum is no greater than those estimates now current and based on stratigraphy. The important conclusion is that time since the beginning of the Cambrian is from ten to fifteen times longer than has been generally accepted by geologists.

Surprising as it may seem, the date known with the greatest precision lies far back in pre-Cambrian time. From Norway, Texas, Quebec, and German East Africa uranium minerals associated with granites give an age which approximates to 1,120,000,000 years. In the Scandinavian nomenclature the granite is post-Bottnian. In Quebec it is later than the Laurentian granites and is probably post-Sudburyian (post-Temiscaming).

This is the age, consequently, of the second great granitic invasion of known geologic time. The Laurentian granites, the first great invasion, may have an age as great as 1,400,000,000 years.

These measurements of the length of the several eras give a basis for estimates of the mean rates of erosion and sedimentation. In the pre-Cambrian they point to the existence of long periods of quiet, during which the continents were baseleveled. The profound revolutions, marked by folding, magmatic invasion, and regional metamorphism, were relatively brief periods closing long eras marked by diastrophic quiet and low continental relief.

Another aspect to be considered lies in the relations of organic evolution to this great expansion of time. If it be assumed that the lowest forms of life began shortly after the earth's surface was fitted to support them, then instead of evolution being compressed into less than a hundred million years, it is stretched out over a period of the order of 1,500,000,000 years. A discussion is given of the biologic advantage of this far greater duration for accomplishing the organization of the cell and the establishment of the principles of heredity. Although evolution may advance by saltations and is accomplished through the establishment of new or the dropping of the old mendelian factors, yet the building up of the organization of the metazoa implies the sifting out of favorable combinations from chance variations by a process of natural selection. Only in this way can organisms become organized and efficiently adjusted to their environment. But this requires numberless generations living in the relatively brief times of changing environment and resulting organic stress.

Finally, the recognition of this larger magnitude of geologic time opens up sharply another problem—the source of solar energy. But the sun is only one of the numberless host of stars, and the source of its energy is a far-reaching cosmic problem. To warm the earth through the vast length of geologic time, gravitational condensation of the solar mass is found to be totally inadequate. The energy supplied by the atomic degeneration of uranium and thorium would have ample endurance in time; but, even if the sun were composed entirely of these elements, their decay could not supply the quantity of energy which is daily expended. Geologic time brings to light, consequently, the evidence of unknown sources of energy, cosmic forces which must constitute a fundamental factor in any satisfactory hypothesis of stellar evolution, a factor which has not as yet been taken into full consideration in its bearings. Even if, as a lesser difficulty, it should be sought to deny the validity of the radioactive measurements of the earth's age, escape can not be had from this conclusion, for various lines of purely geological evidence indicate an age many times greater than that which could be granted if the solar energy were due simply to contraction of the sun's mass. The depths of geologic time leave us face to face with the unknown.

PART I.—RHYTHMS IN DENUDATION

PRESENT RATES OF DENUDATION

Sedimentation rests on the rate of denudation. It can not go forward faster than material is supplied, but it may proceed slower, and the balance of the waste be carried beyond. In studying the time values to be assigned to the components of the stratigraphic column, the first problem, therefore, is to discuss the present rate of denudation. By noting the factors which enter into it we may arrive at a truer conception of the variations of denudation in the past.

The mean rate of denudation—the lowering of the continental surfaces by pluvial and fluvial erosion—has long been sought. The usual method has been to measure the waste which representative rivers carry to the sea in the course of a year. The drainage basin of the Mississippi was thus estimated to be lowered one foot in 6,000 years, or adding the dissolved matter, one foot in 4,500 years. These figures have been given considerable weight since the Mississippi has been taken as a representative river.[5] For the measurement of geologic time the mean rate of erosion has generally been taken, however, as higher than this. Goodchild selected one foot in 3,000 years as the best average. Sollas uses a figure derived from Geikie, of one foot in 2,400 years. A more reliable mean figure is based on solvent denudation. The mineral matter carried in solution in river water, and also the quantity of water, can be accurately determined at suitable intervals. By taking representative streams for various climates and topographic reliefs, a mean result is obtained. Valuable figures for the area of the United States have been contributed especially by Dole and Stabler of the U. S. Geological Survey. On the basis of these data F. W. Clarke finds that, taking the continents as a whole, they are lowered by solvent denudation one foot in 30,000 years. This estimate he regards as probably correct within 10 per cent.[6] From measurements of the suspended matter collected in the analyzed samples it is found for the United States that the removal of this insoluble material lowers the mean continental surface one foot in 13,800 years. The rate for the combined action is one inch in 760 years,[7] or one foot in 9,120 years. A number of writers who have used these data have failed to note, however, that the materials transported along the bottom, as sand or gravel, are not reckoned into these results.[8] In such a stream as the Mississippi near its mouth this would involve but a moderate correction, since the great bulk of its material is there carried in suspension and solution. The silt, however, is carried in greater quantity near the bottom. In applying the method to the rate of erosion in the upper parts of river systems, or at the mouths of streams which carry much sand to the sea, a larger correction for purely bottom transportation would be necessary.

The rate varies greatly from season to season, and the volume of suspended matter may vary 50 per cent from one year to another; but, considering the various factors, Dole and Stabler regard the figures for denudation as generally within 20 per cent of the true value. The rate is highly contrasted, furthermore, in different regions. Measurement of dissolved and suspended matter at Yuma shows the Colorado basin, with an area of 230,000 square miles, to be lowered one foot in 5,300 years. The western Gulf of Mexico drainage, with an area of 315,700 square miles, shows the much lower denudation rate of one foot in 21,600 years, but an important correction may be needed in the arid and semi-arid regions for eolian transportation. The amount of denudation increases with high rainfall, but the Mississippi basin shows, nevertheless, a higher rate than the southern Atlantic watershed.

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[5] A. Geikie: Text-book of Geology, 1903, pp. 589-591.

[6] A preliminary study of chemical denudation. Smithsonian Misc. Coll., vol. 56, no. 5, 1910.

[7] Dole and Stabler: Denudation. Water Supply Paper 234, U. S. Geol. Survey, 1909, p. 83.

[8] Dole: See methods of collecting samples. The quality of the surface waters in the United States. Water Supply Paper 236, U. S. Geol. Survey, 1909, p. 10.

Very high rates have been found in mountain regions in other countries, the Po being estimated to lower its basin one foot in 729 years, the Ganges one foot in 823 years. Geikie devotes a special heading to "The unequal erosion of land."[9] He calls attention to the dependence of erosion upon slope, and that within each river basin the rate varies greatly in its different parts. It seems likely that over the more rugged portions of the mountains in the Po and Ganges drainage area the rate of erosion may be two or five times the mean for the whole of those areas.

Using Clarke's estimate for chemical denudation for all the continents as one foot in 30,000 years and taking this as 30 per cent of the total denudation gives a mean rate of total denudation at the present time of one foot in 8,600 years. This, although reliable as the present rate, perhaps to within 10 per cent, is seen to depend upon the average of a great range in values, both locally and regionally, from ten to twenty or fifty times the mean as one limit to zero as the other limit, or even beyond it to actual deposition. *Any condition in the past which would change the aspects and areas of the lands in the same direction over various continents would change the mean for such times enormously.* Therefore if such a figure, obtained for the present, is used blindly, it is likely to become an extremely misleading unit for the measurement of geologic time. Harker has recently called attention to the lack of value of mean figures which are based on such widely varying data.[10]

RELATIONS OF RATE TO THE CYCLE OF EROSION

Davis in his publications from 1889 to 1892, extending the ideas of baseleveling formulated by Powell and Dutton, showed that the lands had been baseleveled recurrently in former geologic periods. To the resulting topographic form he gave the name of peneplain. Many ancient peneplains are now buried and preserved as surfaces of unconformity; others have been elevated and more or less destroyed by new cycles of erosion as yet uncompleted. In topographic old age the rate of erosion he showed must become indefinitely low.

In 1898 Tarr published a paper in which he brought forward various arguments against the peneplain.[11] One of these rested on the fact that no extensive peneplains, not uplifted or dissected, are known to exist at the present time in any part of the earth, although peneplains were said by Davis and his school to have been produced again and again in the past. Therefore, argued Tarr, we need as a fundamental assumption to believe that during a part of the remote past the conditions have been different from these that have prevailed in any part of the known earth during the present and the immediate past.[12]

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[9] A. Geikie: Text-book of Geology, 1903, pp. 591-593.

[10] A. Harker: Geology in relation to the exact sciences, with an excursus on geological time. Nature, vol. 95, 1915, pp. 105-109.

The following year Davis published a rejoinder,[13] and, in regard to the contention cited above, he stated that here Tarr and he were in agreement, except that he should prefer to replace "fundamental assumption" by "necessary corollary." Davis notes that it was as a very surprising corollary that he came on the difference between the present and certain parts of the past with respect to peneplanation.[14]

Davis's position is now regarded as established, but the significance of this fact of difference between the present and the past is not fully appreciated outside of the field of physiography. The earth has rested time and again in repose; shallow seas have spread far and wide over baseleveled lands: over the greater part of the continental surfaces which remained above the sea erosion must have become reduced to a small part of its present rate. This conclusion, which is fundamental in stratigraphy and in the stratigraphic measures of geologic time, will be developed from other points of view in the following topics.

It is clear that epochs of diastrophism are more or less closely correlated in widely different regions. Changes in sealevel are necessarily felt over the whole earth, increasing or decreasing by relativity the mean height of the lands. But beside this the lands themselves are periodically broadly warped and, more locally, mountain growth takes place. In so far as the relief of the land is simultaneously modified, the stages of erosion cycles in different regions tend to be correlated and the mean rate of denudation for broad regions and even for the whole earth may vary in the same direction.

The rate of denudation increases through the stage of topographic youth, reaching a maximum when all of a drainage basin has become dissected and given a maximum of sloping surface. From this mature stage the rate decreases as the elevation of the interstream areas are lowered, and finally nearly ceases in topographic old age. It is important, however, that this law of variation should be examined in more detail, for much depends on it, especially as the writer has recently heard it stated by an able geologist that in his opinion the angle of slope had but little influence; the rate, on account of various compensating factors, continuing, in his opinion, high until old age was attained. This geologist pointed out as evidence that lowland streams may be silt-laden and show a high rate of denudation, whereas mountain streams are clear. Without denying these facts, the writer would give them a widely different interpretation and holds that denudation *in the same rock formation* varies with the slope, and probably at a somewhat higher rate than the change in the angle of slope. The problem is complicated and the relationship must vary with climate and rock formation. It is not as yet susceptible of precise statement. To the writer it appears probable, however, that the rate of pluvial and fluvial denudation in the same formation and under constant rainfall varies between the first and second power of the angle of slope.

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[11] R. S. Tarr: The peneplain. American Geologist, vol. xxi, 1898, pp. 351-370.

[12] Loc. cit., pp. 353, 354.

[13] W. M. Davis: The peneplain. American Geologist, vol. xxiii, 1899, pp. 207-239.

[14] Loc. cit., p. 221.

A strong argument that the rate of denudation varies with slope is derived from the nature of the profile of a graded stream and of the cross-section of a mature valley as developed in a single erosion cycle.

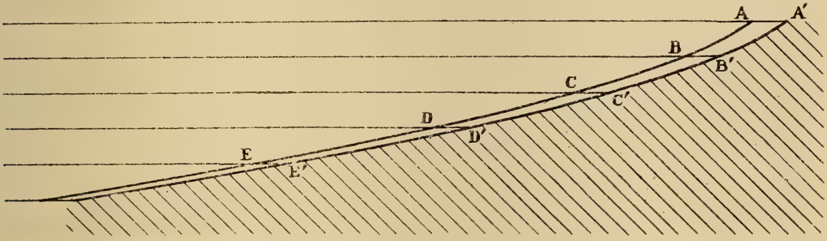

FIGURE 1.—*Stages in a graded Valley Profile cut in a homogeneous Formation*

A valley profile, if a graded slope in a homogeneous rock, is a curved slope, as shown in figure 1. Let A E and A′ E′ be two successive stages in the erosion of the valley, stages sufficiently close so that the character of the curve does not change in the interval. Then A A′ = B B′ = EE′. Let equal contour intervals A B, B C, etcetera, be taken and the volumes of rock, A A′–B B′, removed between each contour interval are equal. But the erosion *surface* A B for the unit volume of erosion on the steep slope is very much less than for D E on a flat slope. Therefore the rate of erosion on the steep slope per unit of surface area is proportionately greater.

This argument is strictly true for the parallel walls of a valley. For the circumference of a basin, however, there is really a larger volume of rock between the upper contours. For hills situated within the drainage basin, on the other hand, there is a lesser volume. This and the lesser erosive power of the rain not yet gathered into rills gives such hills a convex profile across the top as the profile of equilibrium.

It is seen further that the main river, with its greater volume of water, comes to flow on a flatter slope than its tributary, and thus there is an adjustment in equilibrium. The erosion of a soft formation on a flatter slope is in adjustment also with the associated hard formation with a much steeper slope.

Another line of evidence on the large influence of angle of slope is seen in the geological speed with which the early stages of a new erosion cycle are completed. On a new pulse of uplift the river becomes entrenched near its mouth and this entrenchment migrates toward the head waters. It advances far up the stream and changes from youth to maturity, while the older part of the valley has changed its character but little. River piracy is another result of the same effect. If a river obtains an advantage in depth it will cut into the basins of other rivers rising from the same watershed. The steeper slopes enable it to remove much more material in the same time interval, and this is a necessary condition for river piracy, although after the capture is effected the added water then gives the river still greater corrasive power.

The pluvial, or stream profile, and the fluvial, or cross-profile, of a valley must show different relations of rate of erosion to angle of slope. The stream profile is not only cut much faster, but is long and flat and in equilibrium with a valley cross-section of far higher slope. The result is seen in the rapid cutting of gorges as the initial effect of uplift, followed by the far slower weathering back of these, accompanied by only a slight further flattening of the stream profile. Flowing water has been theoretically argued to erode as the square of its velocity, and its moving force to increase with the sixth power of the velocity. Gilbert found from experimental work that

> "for each combination of discharge, width, and grade of debris there is a slope. called competent slope, which limits transportation. With lower slopes there is no load, or the stream has no capacity for load. With higher slopes capacity exists; and increase of slope gives increase of capacity. The value of capacity is approximately proportional to a power of the excess of slope above competent slope. If S equal the stream's slope and δ equal competent slope, then the stream's capacity varies as $(S-\delta)n$. This is not a deductive, but an empiric law. The exponent n has not a fixed value, but an indefinite series of values depending on conditions. Its range of values in the experience of the laboratory is from 0.93 to 2.37, the values being greater as the discharges are smaller or the debris is coarser." [15]

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[15] G. K. Gilbert: The transportation of debris by running water. Prof. Paper 86, U. S. Geol. Survey, 1914, p. 10.

From these considerations it appears that the corrasive power of a stream varies perhaps near the square of the slope.

On the waste slopes leading down to the stream the component of gravity varies with the sine of the angle of slope. For slopes low enough to hold soil it may be said to vary with the angle of slope, as the sine and its arc for small angles are approximately equal. The greater time taken to remove the material from a flat slope is shown by its reduction by weathering to a finer state. In humid regions this soil becomes bound by vegetation which prevents a ready washing away, even though reduced in size of particle. Where the lateral slopes of valleys in humid climates are mantled with clastic material the rate of removal probably varies between the first and second power of the angle of slope. It cannot, however, obey any regular law, but varies with many factors.

The action of ground water must be considered as an important factor. In humid climates it is most important as the preparatory agent in mechanical erosion as well as in solvent denudation, but to be effective it must circulate, not lie stagnant, and for circulation there must be "head." Where the head is high with respect to the length of course, the velocity of underground flow increases. The maximum rate of chemical decay is therefore produced in a well dissected country, but one with slopes flat enough to hold soil and prevent a high ratio of surface run-off to total rainfall. Deeply incised valleys are a factor favoring rock decay, but very thick soil mantles act, on the contrary, as a check to further decay and testify to the efficiency of the natural vegetation to prevent soil waste rather than to a high rate of present chemical denudation. Denudation in such regions is potential rather than actual. In a topography of considerable relief the stimulus of more rapid circulation of ground water causes the zone of oxidation as well as that of hydration to affect a greater volume of rock. Much of this water returns to the surface to swell the volume of the main streams and give them increased carrying power. With very steep slopes, however, there is a lesser proportion of ground water to run-off, but if the intervening hilltops are flat from a previous cycle of erosion, then there is not only abundant ground water, but a more vigorous circulation.

It would appear on reviewing the complex factors that the rate of chemical denudation does not vary with slope to such a high degree as does mechanical denudation. In fact, the steepest slopes are unfavorable. On the other hand, a considerable head promotes chemical denudation.

The conditions for limestone regions are exceptional and quite different from those of compact igneous rocks. In limestones a vigorous circulation and solution by underground waters may go forward with moderate head, whereas the bare and steep outcrops have superior resistance. In humid climates, consequently, areas of limestone advance to the peneplain stage with great rapidity. In mountainous regions with semi-arid climate, on the contrary, they constitute formations much more resistant than those of shale, standing out above them as more or less prominent ridge-makers.

Let attention be given next to the nature of ground-water action under a peneplain. The conclusion would appear to be opposite to that which has often been advanced. It has been frequently postulated that a peneplain would become mantled with a very deep residual oxidized soil, and that on uplift this disintegrated cover would be rapidly removed and swept into depressions. The red color of the Triassic of the eastern United States has been explained in this way by I. C. Russell and B. Willis and it has been applied to the Potomac deposits resting on a Jurassic peneplain. It seems clear, however, that the very thickness and coarseness of these deposits and the great abundance of fresh feldspar in the Triassic show that erosion went on with uplift and that the material was not greatly weathered. Furthermore, beneath a typical peneplain there should be practically no ground-water circulation. The pore space of the ground will be well filled with water, but there will be no head to give it circulation, and as soon as the water becomes saturated all further solution stops.

Peneplains, then, should possess a relatively thin regolith. The conclusion is of some importance in the explanation of the fresh and clean rock surfaces below disconformities. These planes of separation extend over great areas between the strata of different periods. They represent land intervals, yet when the sea returns the new deposits almost invariably rest on fresh rock. Some reworking of a regolith by marine abrasion doubtless occurs, but the absence of a heavy debris as a bottom sandstone and shale indicates in many cases that this is not important.

All rules have their exceptions, and the truth or error of this general principle, based on the laws of hydraulics, should not be regarded as tested by an individual case. The preceding discussion has assumed a homogeneous rock-floor, and this in many examples not the fact. First, such a formation as the Dakota sandstone leads ground water to great depths below baselevel, and even in advanced stages of the erosion cycle enough head would still exist to give a flow, though feebler than in a stage of higher relief. Second, waters sinking into residual uplands would in places find their way far out under peneplains before rising to the surface. Third, many of the irregular deeper parts of the weathered belt. decomposed during the vigorous circulation of the mature stage of the erosion cycle, would be preserved as fossil remnants of an older belt of weathering beneath the surface of a peneplain, though no longer serving as zones of underground flow. Facts which appear to require such exceptional interpretations are known, but as long as they are isolated examples they can not be used as arguments against the generality of the principle.

Thus a very flat emerged plain in time would come to have its unconsolidated sediments removed down to baselevel. Below that level cementation rather than solution would go forward, and close below the surface would exist conditions for the indefinite preservation of limestone, fossils, and other soluble materials. Thus on peneplains not only has the mechanical erosion become reduced, but solvent denudation from groundwater action is also reduced to a minimum.

To sum up this discussion, it is seen that no simple law can be given which expresses the relation between rate of denudation and slope. It varies with the absolute magnitude of uplift, and probably, for the average rock and pluvial climate, the exponential factor lies between the first and second power of the angle of the slopes. Thus a region whose surface has an average relief of five degrees probably suffers denudation between two and four times as fast as it will when its average relief is reduced to two and one-half degrees.

Upon the first recognition of the existence of uplifted and dissected peneplains, the date of the older was generally placed as Cretaceous. More recent investigation shows that in regions of moderately soft rocks the oldest recognizable peneplains are hardly older than Tertiary, and may even be late Tertiary, in age. Stages of partial peneplanation of soft rocks and of mature valleys in hard rocks are even younger, belonging to the late Pliocene or early Pleistocene. The Cenozoic is now regarded as an era of general continental elevation; yet from the evidence of the long duration of these partial cycles of erosion the average slope of most parts of the earth's surface due to erosion might be placed as perhaps twice as steep now as during the mean of Tertiary time. The present rate of denudation may therefore be several times the mean rate for the entire Cenozoic.

SIGNIFICANCE OF PRESENT VALLEY FORMS

Over the greater parts of the continents the rivers are now trenched in inner valleys. Rock walls or bluffs more or less narrowly hedge them in. Above the inner valley lies a higher and wider outer valley whose floor represents the level of the stream previous to the last acceleration of erosion. Terraces on this older valley margin or hills with accordant tops give traces of still higher and older levels. The highest level commonly shows a degree of completion of this oldest erosion cycle which is represented by a peneplain. At any one place the evidence of three successive levels is usually all that can be observed and discriminated; often but two may be detected. The relations are best seen where hard rocks rise to moderate heights, as in plateaus not far from the sea. There, as in the Appalachians, the streams respond quickly to the new upwarps of the land, or possibly what may be equally concerned, new sinking of the sealevel. The hard rocks, because of their resistance, survive for a greater time and record a greater number of pulses of diastrophism. The profile of figure 2 brings out the significance of slopes in a diagrammatic form.

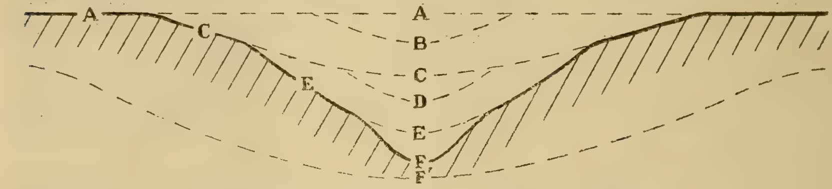

Figure 2.—*Diagrammatic Section of Valley*

Showing composite slope resulting from pulsatory uplifts in quickening periods

In parts of the Appalachians, particularly in southern New England, where broad terranes of metamorphic rocks occur, successive baselevels are recorded by means of peneplains or valleys at successive elevations which average about 200 feet apart. Successively older ones appear in passing into the mountains. There they become more obscure, and it becomes more difficult to discriminate between them or detect accurately their original differences in elevation. The writer sought the approximate dates of these baselevels by tracing the erosion planes into New Jersey, Pennsylvania, and Maryland, opposite to where the formations of the coastal plain attain a wide exposure. By projecting from opposite directions the slopes of these baselevels recorded by erosion and the slopes of the formations recorded by deposition where they approach nearest, the two series were interrelated; but the formations have their dates fixed by fossils, and this leads in turn to the dating of the erosion forms. Those below 500 feet in elevation are the Columbia group of Pleistocene age. Those beginning with the Lafayette or Appomattox and rising higher are Pliocene. Back of the Pliocene series are more dismantled forms which belong to the older Tertiary and even to the upper Cretaceous.[16] Figure 2 shows the type of valley profiles which pertain to the

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[16] Joseph Barrell: Piedmont terraces of the northern Appalachians and their mode of origin. Post-Jurassic history of the northern Appalachians. Bull. Geol. Soc. Am., vol. 24, 1913, pp. 688-696. The burden of other work has prevented up to the present time the elaboration of this subject beyond the first brief publication.

Pleistocene-Pliocene series, but for the upper and outer parts of the river systems which show the older stages the slopes are in general proportionately flatter.

We may turn next to a discussion of these relations of successive stages of valley cutting. On tracing the streams toward their sources, the intrenchment F from the last uplift is found to become shallower and eventually disappear. In the progress of headward erosion the intrenchment from the last uplift has not had time as yet to reach to the upper waters of the river. There the valley section E is higher, narrower, and younger. In long streams, or those rising in the resistant terranes of mountain regions, where the movement has been uplift without warping, several of the latest stages of uplift may not yet have been felt. There one stands in a Tertiary cycle of erosion, still in uninterrupted progress. In order that the successive profiles should be cut, the younger within the older, the oldest cycle, C, must have been the longest; E the next longest, and F the most brief. This kind of a record implies an increasing rapidity of recurrence in diastrophism.

This is a conclusion with far-reaching implication which should be tested carefully. Let us examine, then, some other points of view.

If the present baselevel should endure for a sufficient time, the streams will sink to a flatter grade, the valley slopes flatten down, and profile F change to F′, destroying the previous record; but since we can not look into the future, the nature of the series must be decided on the basis of the record of the past. That record is shown in the relations of A, C, and E, and these indicate an increasing rapidity in the recurrence of uplifts.

These uplifts need not, however, have been simple and free from short period minor oscillations. As shown in broken lines in figure 2, a short pause, B, may have existed and yet had the evidence of its existence totally destroyed by a longer pause, C, and another, D, by a longer pause, E. Even the development of peneplains does not require an age-long freedom from movements in baselevel. Minor oscillations may continue, but they do not in that case lead to a progressive rise of the land. In the lower portions of the river systems alternate fill and scour of the valley would take place, but in the upper parts or on the interfluvial slopes erosion would still continue and increase the perfection of the peneplain.

This discussion leads us back to the significance of the quickening series shown by the present valley forms. The quickening is especially in regard to the Pleistocene movements. For certain of those of Pliocene or older date no such hypothesis of acceleration may be necessary, since each new intrenchment below an old peneplain before the previous cycle had become advanced gives a greater thickness of rock above baselevel, and will require a longer time for the cycle to become completed. If the stages of uplift were equally spaced, the first cycle of rejuvenated erosion would advance farther, there being less rock to be removed. Nevertheless the whole of the younger series, if the erosion due to them is not well advanced, must be embraced in far less time than that which led to the development of the peneplain.

Turning to the shore, the Pleistocene history shows that the aggregate motion of uplift has been not merely discontinuous uplift, but that movements of submergence took place between each emergence, and the land at the present time is in a submergent phase, but not necessarily now in movement. A submergent phase is felt as a stagnation of drainage and marked alluviation on the valley floor for a short distance above the actual drowning of the river mouth. Farther upstream, however, there is but little change in the grade of the stream, and the headward erosion from the previous intrenchments of the rivers continues.

Thus, although the problem involves a number of factors, these do not change the direct and simple interpretation of the significance of the Pleistocene-Pliocene series of valley slopes. There have been aggregate uplifts by movements which on the whole have increased in rapidity, and notably so in the Pleistocene. Over the Atlantic coastal plain of the United States the submergent phases of the Pleistocene movements are represented by deposits more or less eroded, the older showing much greater erosion than the younger. In Maryland, the Lafayette, late Pliocene in age, attains, on the low plateaus facing the sea, a maximum elevation of 500 feet. Up the stream valleys the river grades carry it to higher elevations. The Lafayette Valley forms correspond to C of figure 2. The next younger deposit is known as the Sunderland. It belongs to the older Pleistocene and shows wave-cut terraces reaching to 220 feet in elevation. Farther inland the valley profile corresponds to E of figure 2. The middle or later Pleistocene wave-cut terrace is the Wicomico, reaching to 100 feet in elevation. Its corresponding valley form is F. A number of glacial geologists have estimated the time necessary to cut these valley profiles, and agree that it increases backward in geometrical progression. If F was cut some tens of thousands of years ago, E was cut some hundreds of thousands of years since, and C would appear to date back more than a million years—possibly two million, possibly several million. McGee, in fact, is inclined to estimate post-Lafayette time as from five to ten million years in length.[17]

The Pleistocene need not, however, be regarded as unique in showing such an accelerating series of uplifts. Similar series must have occurred in the past, leading up to the crises of diastrophism in periods of revolution, but they must have been followed by retarding series and long periods of quiescence. The uniqueness of the Pliocene-Pleistocene movements lies rather in the great mean heights which the continents have attained.

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[17] W J McGee: Note on the age of the earth. Science, vol. xxi, 1893, p. 309.

Having discussed the time relations of the late Pliocene-Pleistocene series of movements, attention should be turned next to the effect of such a quickening series of uplifts on the aggregate rate of erosion.

An uplift steepens the grade near the mouth; headward intrenchment follows up the main stream and its tributaries. As the area of dissected and steepened slopes increases, the quantity of material eroded increases; but as time passes the slopes flatten down, the maximum rate of erosion due to that pulse in that part of the river passes away, and the rate enters on a descending curve which approaches the zero line, but unless disturbed by other factors never reaches it. The second uplift, however, produces another wave of erosion, which follows upstream after the first, but does not catch up to it. It deepens and steepens the valley floor and increases the average slope of the region. In the mountains the erosion in stages due to Pliocene uplift is still at work, and the quicker and younger Pleistocene pulses of uplift have not been felt.

Over wide belts of soft rock and on the plains the present stimulus to erosion is due to the Pleistocene uplifts. The rivers flow in inner valleys bounded by bluffs usually 100 to 200 feet in height. The valley uplands may be several hundred feet higher. These movements have occurred with such geological rapidity that in such regions ground-water action has become greatly favored, because the flat interfluvial tracts serve as catchment areas and the deep intrenchment gives the ground water opportunity for circulation. As the bedrock of many such plains is calcareous the actual rate is very high. Even in regions of low or moderate elevation the rate of erosion may temporarily exceed that of the mountain regions. The average angle of slope may be as high also as in the mountains. The latter owe their bold relief to the continuity of slope for longer distances rather than necessarily to a higher average angle of slope.

Erosion of the lowlands has received still another acceleration in the United States within the past two centuries, and in other lands during a longer period, due to the interference of man with nature. In the United States, especially, the run-off of soil, due to careless agriculture, has become in many sections a national scandal. Deforestation of steep slopes with loose soils, followed by plowing and overgrazing, makes the rivers turbid after each rain and has already impoverished considerable areas.

The high rate of erosion of lowlands is indicated by the figures for denudation obtained by Dole and Stabler. A difference between these and the mountain regions would become apparent in time if the diastrophism were to enter on a slowing pulsation or to cease altogether. With geological rapidity the lowland valleys would widen out, the average slopes become much reduced, and the rate of erosion fall to a fraction of its former rate. In the mountains, on the other hand, erosion would continue with undiminished rate for a time and would only slowly diminish, the mountains remaining mature long after the lowlands had become old.

The conclusion that the Pliocene-Pleistocene movements are members of a quickening series is evident for the Atlantic shores. Around the Pacific the movements are on a more prodigious scale; but there again, especially in the Andes, is seen the evidence of great intrenchment of the rivers flowing through profound gorges. Thousands of feet above is an older mature topography that speaks of a long time of quieter crust and lessened rate of erosion.

The present rate of denudation of the lands may then be twice or thrice the average for the Cenozoic and five or ten times the average for earlier periods. Nevertheless, many ancient sedimentary formations testify to rivers as swift as those of today. The Old Red sandstone consists of deposits analogous to those now forming in Cordilleran or Eurasian intermontane basins. Such formations are, however, relatively local. They are, furthermore, recurrent, not continuous, in time. They emphasize by contrast the low rates and limited areas of denudation characteristic of intervening periods.

The association of glaciation within periods of revolution indicates that one of the ulterior causes of glacial climates lies in diastrophism. The individual advances and retreats of the continental ice can not, however, be correlated with individual crust movements; nevertheless, it is suggestive of the quickening diastrophism that the Glacial epochs appear to have been more quickly recurrent in the later Pleistocene. The relative remoteness of the Glacial epochs is given by Chamberlin and Salisbury as follows:

From the late Wisconsin to the present	1
From the early Wisconsin to the present	2 to 2½
From the Iowan to the present	3 to 5
From the Illinoian to the present	7 to 9
From the Kansan to the present	15 to 17
From the sub-Aftonian to the present	X [18]

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[18] Chamberlin and Salisbury: Geology, vol. iii, 1906, p. 414.

Long intervening periods of warmer climate seem to show that this is in reality a converging series and not merely an effect of perspective, from a point of view unable to see the full record of the farther past.

Thus from the oscillations of climate, as well as from the signs of unrest in the crust, there is seen to be no evidence that the culmination of the present period of terrestrial revolution is past. The evidence is suggestive, not definitive; but the indications of the quickening series are that, although at the geologic moment the crust is in a minor submergent phase and the climate of interglacial character, yet the crisis may be before us, not behind us. Men have taken hope that the Ice Age is past and have looked on the Quaternary revolution as closed; but the study of the rhythms robs us of that assurance. At several times in the Pleistocene that view, as based upon apparent subsidences of crustal and climatic movements, would have been far better justified by the evidence than it is at the present moment. The high latitudes, unlike their state through the most of geologic time, are still mantled with glaciers. The shorelines are now in a stage of earliest youth. We live, in fact, within the Age of Ice, within an age of crustal unrest and revolution; the geologic morrow may bring forth greater and more compelling changes than the geologic yesterday.

CONTRAST OF CENOZOIC AND PALEOZOIC CONTINENTAL RELIEFS

The present mean elevation of the lands is approximately 2,400 feet, and Murray, in 1912, places their area at 59,870,000 square miles. The waters with a depth of less than 600 feet surrounding the lands cover 10,000,000 square miles. Taking this area of shelf seas as part of the continental platforms, the continents are now six-sevenths emerged. Reckoning in these margins does not, however, give a just comparison with the attitude of the land-masses during the spread of epeiric seas. It is rather the continental interiors which offer the more significant contrast. The floor of the shelf seas forms the continental terrace, which is in considerable part the result of a sedimentary outbuilding. Suppose the sealevel to sink 600 feet. If the movement were moderately slow, the construction of a new but narrower submerged shelf would keep pace with the uplift. The unconsolidated deposits of the present shelf seas, exposed to erosion by uplift, would be planed down with great rapidity by river action and wave action, new waste from the land would also be contributed, and thus a submerged shelf would be maintained.

The present epeiric seas of northwestern Europe and northern North America are not comparable in cause to the Paleozoic seas. The Baltic and North seas and Hudson Bay show a close relation to the lowlands which were covered in the late Pleistocene by continental ice-sheets. These shallow-water bodies appear to be, consequently, lingering effects of the local depression of the crust under the weight of the ice.

Eliminating these special conditions, let the continents be contrasted with their past states in amount of submergence, and it is seen that not only is there a notable absence of internal floodings, but a very notable elevation of the continents as a whole.

The great contrast between the present broadly elevated lands and the low and flooded condition of the continents during epochs of geologic quiet marks out the later Tertiary and the Quaternary as together constituting a great period of revolution. This, as a general statement, is well appreciated, but certain of the logical consequences have not leavened geologic thought.

The ancient epeiric seas were typically very shallow-water bodies. The evidence is clear and varied. The lime-depositing seas have formerly been regarded as the deepest, yet bottom-growing algæ were at times abundant, as seen in the cryptozoan horizons. Sunlight must therefore have freely penetrated to the bottom. But more emphatic testimony is given by interformational conglomerates, which show during the deposition of the beds a vigorous stirring of the bottom by wave action. Still more positive in meaning are the mud-cracks which are abundant in certain horizons. These are not shore phenomena, since they may occur at the same horizon over areas reaching thousands of square miles; neither are they of tidal origin, as shown by their breadth and the absence of tidal channels. With seasonal change of winds, or more probably with slight oscillations in level of longer period, the water came and went.

The wide-spread marine sands and silts of these seas show the effectiveness of wave action in agitating the bottom material and working it by oscillatory action to great distances. Over a broad reach of shallow water the wave action is adjusted to depth, being damped down by the work of stirring the bottom. Furthermore, in times of equable climates, although the circulation of air and water was very effective in distributing the equatorial warmth to high latitudes, yet the intensity of winds was probably less. Winds are due to differences of temperature and pressure and are in general most intense where these conditions rise highest, as in middle temperate latitudes in winter. The wave action in the epeiric seas was then more comparable to that which now exists over broad, shallow lakes or bays in the warmer climates rather than comparable to the waves of the deep and open oceans.

From these lines of evidence depths of 20 and 50 to 100 feet may be regarded as typical. Occasional deeper waters must of course not be excluded. The fact that these shallow seas were not speedily filled with sediment and converted into river plains shows that erosion was slow. The greater areas of the land were flat and but little above the sea. Mountain axes alone were the regions of pronounced relief. The retreat of the seas from the continents required a falling sealevel of not more than a hundred, or at the most a few hundred, feet. Over broad land areas the elevation was so slight and drainage was so sluggish that when the seas returned they commonly came to rest directly on the uneroded sediments of the previous periods. During the land interval, if it was more than most temporary, the layers of unconsolidated sediment above baselevel were washed off and the evidences of the farther advances of the previous seas were destroyed. Nevertheless this erosion was very limited in depth and speaks of the limited elevation of such lands required to drain the seas. During the Paleozoic and to a lesser degree in the Mesozoic the mean sealevel was evidently notably higher with respect to the continents. Even in the periods of revolution, although mountain systems were made and the epeiric seas withdrawn, yet the continents outside of the mountainous regions still stood low. This is illustrated by the very broad expansion of Ordovician deposits not eroded in the Taconic disturbance, but covered by the Silurian and later sediments. During the Devonian there was intense mountain-making and igneous activity. Basins were filled many thousand feet deep with continental sediments, yet marine waters persisted rather widely over the interior of the American continent. Further orogenic movements in the late Mississippian (Chester) and again in the late Pennsylvanian led to vast deposits of waste, but these were laid down broadly as interbedded marine and continental deposits on the continents, not carried by rivers to the margins. Even the Permian revolution was attended by so little elevation of the continents that, although the seas withdrew, vast areas of sediments of the previous period were preserved with their stores of coal to the age of man. These coal fields are now in considerable part above sealevel, are undergoing extensive dissection, and the completion of the present cycle of erosion would greatly reduce the quantity of Carboniferous coal even without the exploitation by man.

On the other hand, this argument must not be pushed too far. The farthest extensions of the ancient seas left thin deposits which have been stripped back to later and lower baselevels by the erosion of all later time; the lesser extensions, on the contrary, have had their deposits protected by blankets of later sediment. The limitation of present outcrop is consequently no evidence of the original limitation of the formation. That must be determined, in so far as it is possible, mostly by means of the internal evidence of the sediments themselves and the entombed faunas and floras. Schuchert assigns to the lowest Trenton sea a flooding of 57.2 per cent of the present land area of North America, the widest inundation of geologic time. To the Cretaceous sea he gives a maximum spread of 41.3 per cent.[19] Schuchert's maps are of great value because each represents a limited period of time and the shores are drawn as close to the limiting outcrops as is permissible. As he recognizes, this tends to make the areas of the seas too small, but increase of knowledge will show where and to what extent the boundaries must be extended. These facts must not be forgotten in using the maps. Considering the inevitable cutting back of outlying outcrops in cycle after cycle of erosion, it appears to the writer that the lowest Trenton sea probably covered as much as 65 or 70 per cent of North America and the Cretaceous seas and deltas at their maximum probably 50 per cent.

Another significant feature in interpreting the mean attitude of the continents in the past is found in the fact that the mantle of sedimentary rock, made up by formations of different periods, is wider than the deposits of any one sea, this statement applying to other continents as well as to North America. To what degree is this composite mantle, accumulated through earlier periods, now subject to destruction by a reversal of the balance from deposition to erosion? To answer this we may compare the areas of ancient marine sediments relative to the areas now undergoing marked denudation.

The area of the land is 60,000,000 square miles. Of this it is estimated 20.3 per cent,[20] or 12,000,000 square miles, expose Precambrian rocks; 48,000,000 square miles are of sedimentary rocks or of eruptives which mostly overlie sediments. As to elevation, 18,000,000 square miles, or 30 per cent of the land, lies less than 600 feet above the sea and may be taken as the lowland area. It is at the present time subject in part of its area to erosion; in part it is receiving delta and basin deposits. The remainder of 42,000,000 square miles of land is above 600 feet in elevation and is subject to more or less vigorous erosion. If, leaning backward in the argument, all the Precambrian should be assumed as within this upland area, there would still remain 30,000,000 square miles, or one-half of the continental surface, which consists of ancient sedimentary formations, mostly marine, which in the later Tertiary and Pleistocene have been uplifted more than 600 feet, in part to several thousand feet, and subjected to rapid and deep denudation. If the present erosion shall persist into the stage of old age, great areas of Paleozoic and Mesozoic sediments will have become destroyed. But nature reveals while she destroys, and because of this very fact of the contrast of the present to the past the comprehensive study of the stratigraphic record is made very much easier than it would have been in the average condition of the lands, and in this particular century has been further facilitated through the fresh exposures made by man incidental to his development of transportation systems.

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[19] C. Schuchert: Paleogeography of North America. Bull. Geol. Soc. Am., vol. 20. 1910, p. 601.

[20] Von Tillo: Comptes Rendu. Paris, vol. 114, 1892, pp. 246, 967.

The existence of a mantle of sedimentary rocks, mostly marine, covering three-quarters of the land surfaces, proves that since the opening of the Middle Cambrian these portions of the continents have on the whole received sediment rather than supplied it. Of course, there has been alternating deposition and erosion. Unknown amounts are gone, but the balance was in favor of accumulation of sediments. Marine shales and limestones are the most wide-spread of formations. Through most of geologic time the continents have lain awash with the ocean level and across them the rising ocean floods have flowed. The sediment of these Paleozoic and Mesozoic times came in greatest bulk from the limited

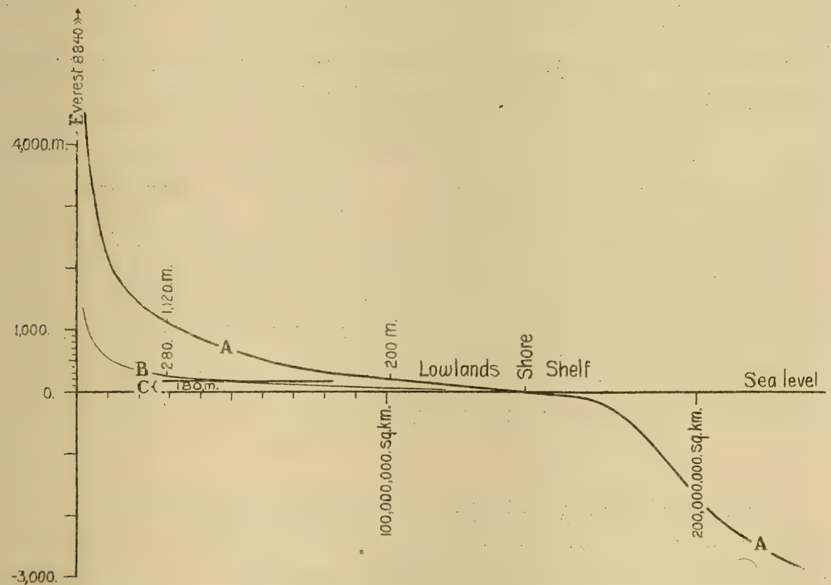

FIGURE 3.—*Hypsographic Curve of the Continents and its Relation to the Past*

A. Curve of continental relief, showing relations of altitude to area.

B. Curve giving one-fourth relief, representative of periods of wide epeiric seas.

C. Limits of periodic oscillations of sealevel to flood two-thirds of continental area with profile B.

areas of mountain systems, repeatedly worn low. A lesser portion came from the reworking of older sediments from the gently upwarped portions of continental interiors. On these the erosion cycle was carried to such completion during each period that when the waters spread over these lands again the sediment was deposited on level surfaces of disconformity. In these last stages of baseleveling the work of erosion must have become extremely slack.

The evidence of the sedimentary mantle points, then, to the conclusion that the ocean level has stood lower in the Pliocene and Pleistocene and the continents higher, with a more varied relief than they had previously attained since the Precambrian. In figure 3 this conclusion is given graphic expression.

Curve A is the hypsographic curve, or curve of the present continental relief, taken from the statistics given by Penck, as follows:

Continental Relief

Zones of altitude	Relative areas
Below sealevel	0.6
0 to 200 meters	29.2
200 to 500 meters	27.1
500 to 1,000 meters	19.0
1,000 to 2,000 meters	16.4
2,000 to 3,000 meters	3.6
3,000 to 4,000 meters	2.1
Above 4,000 meters	2.0
	100.0

Our knowledge of the general nature of the hypsographic curve for the Paleozoic periods of recurrent epeiric seas is drawn from the facts previously discussed. During the very widest spread of seas two-thirds of North America is taken as covered and the mean depth of the epeiric seas is assumed as 300 feet, or 90 meters. During the emergent stages between the Paleozoic floods, if the land is assumed to have become drained to the present degree, the slopes of the land would nevertheless be so low that two-thirds of its area is regarded as having been less than 600 feet above sealevel. A hypsographic curve to fit these conditions is obtained by dividing the ordinates of the present curve by four. This is shown as B, figure 3, and it brings out vividly and graphically the great contrast in land relief which the preceding discussion has indicated as existing between the present and certain past periods.

In this diagram the sealevel has been kept for convenience as a constant datum. It is probable, however, that the sealevel has sunk since the

Paleozoic as much as 300 to 500 meters with respect to the continents, and that the present average elevation of the lands, 730 meters, is in large part due to that fact. Such a sinking of the sea, due to increase in the volume of ocean basins, is suggested by the gain in height by every continent and the present approach to isostatic equilibrium for each continent as a whole. In order to represent Paleozoic conditions, B and C should then be elevated 300 to 500 meters with respect to A. This would bring the two curves, A and B, of land relief closer together, and if A represents a fairly close approach to isostasy, would minimize the isostatic strain which is implied by the flatness of the Paleozoic lands and permit more readily the control of their level by sealevel rather than by isostatic rejuvenation. The change from the types of Paleozoic to Cenozoic continental reliefs has, then, been accomplished by an increase in the volume of the ocean basins attended by a warping down of the negative areas of the continents several hundred meters and a warping up of the positive areas to a somewhat greater amount. This tendency to differential warping existed in the Paleozoic, but a marked relief was not attained because erosion of the positive areas led to leveling by sedimentation on the negative areas. The tendency to rise of sealevel during a single cycle of continental erosion—a geologic period—may be due most largely to the displacement of sea-water by sediment; the rise during the Paleozoic era may better be ascribed to the addition of juvenile waters. This latter cause has continued in operation in later time, but has been more than offset by an increase in volume of ocean basins and consequent lowering of the mean sealevel, due presumably to continental fragmentation.

CONTRAST OF PRESENT AND PAST RATES OF DENUDATION

The Precambrian ages were of immense duration and broken up into eras by profound revolutions. Sediments were accumulated in great thickness in geosynclines, but over the continents as a whole recurrent erosion exceeded sedimentation. The result was that at the opening of the Paleozoic metamorphic and igneous rocks of the character of those of the Canadian shield constituted the dominant surface formations. To have exposed such rocks the continents must have been broadly elevated and deeply eroded. During pulsatory uplift the rate of denudation doubtless rose at times to the present high rate, and may even have exceeded it, since vegetation could not then have been an efficient binder for the soil. Following such periods of erosion the lands were low and may have rested in that attitude of old age for vast periods of time. In illustration, it appears that following the last great Precambrian revolution the surface, although of low relief, still lay generally above sealevel, the whole of this era, marked by the absence of marine sediments on the lands, constituting the Lipalian era of Walcott. Even in the Lower Cambrian deeply warped geosynclines retained the waste, in part as continental deposits, and not until the Upper Cambrian were the broad expanses of the continents covered by the shallow seas.

Although the seas came and went during the Paleozoic era in periodic oscillation, the thickening and spreading mantle of sediments marks the whole Paleozoic in contrast to the Lipalian as an era of higher mean sealevel. Over the greater part of the continents erosion of a crystalline basement had ceased, and over even the Archean shields it was very slight. Erosion was periodically rejuvenated in mountain regions and doubtless, occasionally and locally, attained rates as high as the present. The aggregate rate for the whole world, however, must have been very low as compared to the present.

The long crescendo of orogenic movements which ended in the Permian revolution gave rise to great mountain systems, but did not materially elevate the continents, as shown by the preservation of broad mantles of Pennsylvanian and Permian sediments. Beginning with the Epi-Paleozoic interval, however, epeiric seas played a less conspicuous part and show by this restriction a somewhat lowered mean sealevel. Triassic marine deposits are scanty; the Jurassic seas acquired a wider spread, but in the Cretaceous the conditions resembled again those of the Paleozoic.

At the close of the Cretaceous another great revolution was inaugurated—the Laramide—and the average elevation of the lands may have resembled that of the close of the Paleozoic. But with the opening of the Neocene the earth's internal forces reawoke to great activity and the present grander mountain systems of the earth began to take their form. The Neocene revolution is so close to the Laramide, compared to the length of the older eras, that the latter revolution may be regarded as a preliminary stage leading up to a crescendo, much as the Pennsylvanian movements preceded and led up to the greater Permian movements. The magnitude of the Neocene revolution is seen, however, not only in the breadth and height of the mountain systems, but in the pronounced warping of the continents, giving a steeper hypsographic curve, and the drawing down of the sea, probably through continental fragmentation, giving a more elevated hypsographic curve. This great height of the continents is a most important feature bearing on the aggregate rate of denudation. There appears to be nothing analogous this side of the Precambrian. The Neocene revolution has continued into the Pleistocene and there is no indication that the culmination has yet been passed.

Looking beyond the coming and going of seas which mark off the periods, to seek out the trends through longer measures of duration, we see an eon-long rise and ebb of sealevel with respect to the continents. It pulsates with the close of eras, falling and then slowly rising again. But from our present elevated continents and lofty mountains, as we look back through geologic time, the eye passes over one system after another, more and more remote, and only dimly on the far horizon do we see in the Precambrian ages a similar relation in elevation of land to sea. This marks the most far-reaching rhythm of geologic time.

But superimposed on this greater rhythm are the crescendoes and diminuendoes of diastrophisms which separate the smaller divisions of time. The Pleistocene represents one of the crescendoes. It has been marked by an acceleration in crustal uplift and oscillation which has raised high the rate of total denudation. Compared to the rate for the whole of the Cenozoic era of revolution, it may be twice the mean. The concurrence of the longer rhythm in sealevel, giving wide and high continents, with the rising diastrophism of a period of revolution may, however, make the present rate of continental denudation ten or fifteen, or even twenty, times the mean for all of earth history, our knowledge of the Precambrian being especially vague. Estimates of geologic time based on measurements of the present rate of denudation and coupled to the assumption that this is the mean for all the past are likely to err correspondingly.

This may seem an abandonment of the principle of uniformitarianism on which the science of geology was founded. Davis, however, saw in the existence of cycles of erosion the necessity of giving a more elastic conception to this basic principle. He has stated the problem well, as follows:

> "Uniformitarianism, reasonably understood, is not a rigid limitation of past processes to the rates of present processes, but a rational association of observed effects with competent causes. Events may have progressed both faster and slower in the past than during the brief interval which we call the present, but the past and present events differ in degree and not in kind. This rather elastic understanding of uniformitarianism seems to me comparatively safe from the objections that have been urged against the more rigid conception that some authors regard as necessarily intended in the writings of Hutton, Playfair, and Lyell, especially safe if the very remote hypothetical past of unrecorded time is not considered."[21]

The conclusions reached in this part are so startling that they should be reexamined before acceptance, in order to see if the present can not be regarded as not so exceptional in geologic time. It is clear that the present rate of continental denudation is very high, owing to a concurrence of factors, but it may be conceded to have been somewhat higher at recent times in the Pleistocene. Going farther back, it is possible that during epochs of very rapid retreat of seas the wash of sediment may for a brief time have equaled or exceeded the present rate, but such an effect would have been very temporary. It is doubtless true that in other revolutions broad areas of land have been uplifted, the older sediments removed without leaving a trace, and deep denudation cut into the foundations. The rate of denudation must have been locally as high as it is in regions of similar attitude at present.

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[21] W. M. Davis: Bearing of physiography on uniformitarianism. Bull. Geol. Soc. Am., vol. 7, 1896, pp. 8, 9.

Nevertheless, although granting such approximations toward the present topographic attitudes, it does seem probable that the present mean rate may be twice the mean for the whole of the Cenozoic and ten or fifteen times the rate for all of geologic time since the opening of the Paleozoic.

To sum up the causes of this contrast of the present with the mean of past time, they are to be found in a notable irregularly progressive increase in volume of the ocean basins, resulting in greater mean continental elevation, in greater isostatic strains brought on the continents as a whole by the deeper erosion, in the existence of a great period of revolution, the Cenozoic, whose culmination in the Pleistocene and Recent is marked by glaciation, and, lastly, the rate has been raised by man through deforestation and agriculture. The mean rate of denudation is a factor which, then, in the very nature of things, is subject to great variation through geologic time and is therefore wholly unsuited to serve as a method of measurement. Qualitatively, however, it is clear that time is far longer than those estimates which have been based on a hypothesis that the present rate is a mean which applies to the geologic past.

PART II.—RHYTHMS IN SEDIMENTATION

GENERALITY OF ACCUMULATION IN SHALLOW WATER

Since the early days of geologic science it has been noted that the greater part of sediments, even where accumulated in a geoscyncline, bear the marks of deposition in shallow water. This is conspicuous on noting the significance of the features which are found abundantly in each type of deposit—conglomerates and sandstones, shales and limestones.

Conglomerates and sandstones show transportation by river currents, waves, or undertow. Only rarely, as in torrential deposits poured in lakes, do they exhibit the marks of rolling down a fore-set slope. On the contrary, most conglomerates are stream deposits, a lesser amount being made and deposited by wave action along shores. The marine sands are spread in even layers and are often ripple- or current-marked, indicating the wide-spread and uniform action of waves on a shallow bottom. Floodplain sands show less continuity and regularity of deposit, indicating a prevalence of shifting currents over deltas and basins.

It may readily be granted that the coarse deposits are of shallow-water origin, but the question of the depth at which the fine-grained sediments are on the average deposited is of more importance. Mud is the most abundant sediment, and shale consequently must be the most abundant rock. A not inconsiderable portion, as is now recognized, has been deposted on river floodplains. Rain-prints, mud-cracks, or other features bear evidences of subaerial exposure and indicate generally this mode of origin. Marine muds where intercalated with layers of sand indicate that they are shallow-water deposits, since the sand can be transported only in limited depths of water. Where the interstratified sands are thin and regular, this feature indicates spreading by wave action and the sediment was deposited at wave-base. In certain formations, on the other hand, in contrast to this interstratified type of mud and sand deposit, both sand and the marks of exposure to the air are absent, the mud consisting of an impalpable material, occurring in thin laminæ which may be paper-thin, and varying in color rather than in texture from stratum to stratum. These are presumably lake or sea deposits made in quiet water below wave-base. Such may be classified as deep-water deposits, but among the shales they are the exception rather than the rule.

Limestones are taken as evidence of clear seas. They have often been regarded as deposited in deep water, but, on the contrary, most of the limestones which are exposed on the continental platforms show by their structures that they were deposited in shallow water. In the older geologic periods the contributions of the cryptozoa, bottom-living algæ, indicate that the bottom was effectively lighted by the sun. Mud-cracks and rain-prints at many horizons in limestones prove recurrent exposure to the air, alternating with submergence in shallow waters, usually marine. Intraformational conglomerates are frequent in calcareous and dolomitic formations. They owe their existence, in at least considerable degree, to the drying and cracking of limestone crusts deposited by cryptozoa or deposited as lime silts which were cemented near the water surface at or immediately after accumulation. The fragments have been rounded and further broken by wave action. The chalk which is exposed to observation was formerly regarded as an abyssal ooze, but is now commonly believed to have been deposited mostly in shallow seas. The evidence is found in the stout-shelled mollusks which occur as associated fossils. These thick-shelled types represent adaptations to relatively shallow water;

the mollusks of the deeper waters, by contrast, do not have to withshand the mechanical agitation of waves, are not so vigorously attacked by enemies, and are characterized by more fragile shells. Limestone beds, furthermore, as in the Carboniferous, are often intercalated between shallow-water shales and beds of coal.

The great bulk of sediments which have been uplifted and exposed to observation were deposited in interior continental seas; only as emerged coastal plains on the outer rims of the continents are the records of shelf seas found. These belong especially to the Cretaceous and Tertiary periods, but they also are nearly always of shallow-water origin. Only exceptionally, by profound orogenic movements, have the deposits of the abyssal fore-set slopes of the continents been elevated and exposed by erosion, and still more exceptionally are the bottom-set muds of the ocean depths heaved upward to the light of day.

Thus the sediments whose interpretation form the basis of earth history have been characteristically deposited with respect to a nearly horizontal controlling surface. This surface of control is baselevel, but for continental and marine deposits the baselevel is determined by different agencies and is a word of more inclusive content than the sense in which it has generally been used by physiographers as a level limiting the depth of fluviatile erosion. Sedimentation as well as erosion is controlled by baselevel, and baselevel, local or regional, is that surface toward which the external forces strive, the surface at which neither erosion nor sedimentation takes place.

This emphasis on the importance of wave-base, as the surface which controls the deposition of sediment in water bodies, makes it desirable to discuss its depth with respect to the water surface. Wave-base is that depth at which the wave action ceases to be strong enough to transport sediment. If the wave action becomes strong the particles of sediment are moved to and fro, upward and downward, with the oscillation of each passing wave. In each lift from the bottom the sediment is subjected to progressive movement by the undertow in one direction, by currents in various directions, by the dragging effect of waves of translation in a landward direction. With a lesser strength of wave action the particles are lifted less frequently and mostly during the forward pulses of waves of translation. An increase in the strength of wave action leads to a down-scouring of the bottom and removal of material to deeper water, especially the finer material. The coarsest, however, may be shifted toward the shore as sand or shingle. During a following weaker phase a silting up of the bottom will take place to the previous level, but the finer muds are still worked seaward. Thus sand is kept on the continental platforms, whereas mud tends in larger degree to be deposited below wave-base on the slopes of the submarine continental terrace.

Wave-base is deeper with heavier wind action, with breadth of water surface, with distance from shore, and with fineness of sediment; a gravel or sand would lie below wave-base, because remaining unagitated, in the same locality and depth where silt or mud would be well within wave-base. Conceive a shallow circular basin of water without outlet. The action of waves will tend to shift the bottom sediment and establish a "profile of equilibrium" with steepest slope near shore and flat in the middle. This profile will vary in magnitude from that which is in adjustment with the rollers of the open ocean to that in adjustment with the wind ripples on the surface of a shallow pool, but for these widely different scales it will remain a curve of the same character. For purposes of comparison the following is adopted as an empirical curve for the margin of a wide shelf sea in mid temperate latitudes with a beach of sand and fine gravel. Far offshore the bottom is taken as fine sand and mud.

Profile of Equilibrium for Shelf Sea

Distance from shore in miles.....	1	2	3	5	10	20	100
Depth in fathoms................	7.5	11	13.5	15.5	18	23	50

For wide lagoons, such as those behind barrier beaches, both ordinates and abscissas of this curve should be divided by about 20. Thus, at a distance of five miles offshore the full depth of about 2.5 fathoms would be attained.

The symmetry of this curve is greatly disturbed by a number of factors which are always present to some degree. The curve is flatter on a shore toward which sediment is driven; undertow sweeps the bottom material in certain directions, giving current effects; variations in storms and in depth of water modify it from one scale to another. In general, the rise of sealevel since late Glacial times, a rise which is generally estimated at as much as 20 fathoms, has overdeepened the ocean profiles and only where there is a great abundance of unconsolidated bottom material has the profile been adjusted to the present higher water level. The lack of recognition of this condition has given a general impression that wave action is effective to a greater depth than is the case. The limit is commonly taken as 100 fathoms. In a few places, as west of the British Isles, this is approximately the case, but an inspection of coast charts in general shows a downward curvature of the bottom profile, indicating the cessation of effective wave action, at about 50 fathoms. Daly, Vaughan, and the writer have come to the conclusion that this would be a better general figure for the effective wave-base of the ocean.[22] This is based on the actual evidence of profiles rather than on the theory of waves, or the ability of exceptional waves to agitate mud in suspension at greater depths.

To gain conceptions as to the depth of ancient interior seas several classes of water bodies must be studied. Stormy epeiric seas are represented by Lake Erie and the North Sea. The full depth of water, so far as wave action is concerned, is attained within 100 miles from the shore. In both of these water bodies there are areas below wave-base which permit an excess of sediment to be swept into such reservoirs, and thus prevent the profile from being shallowed. Quiet epeiric seas are found in tropic waters and are illustrated by the shelf sea east of the Mississippi delta, but more typically by the Persian Gulf.[23] The latter is an epeiric sea which has a central portion unfilled and below wave-base. Large lagoons are represented by Lake Pontchartrain on the Mississippi delta. In addition what may be called playa seas formed recurrently important features in the past. These were annually, or at longer intervals, alternately flooded with shallow marine waters and exposed to the air. Such playa seas are represented at present by the Rann of Cutch, an area of 10,000 square miles east of the Indus delta, flooded from July to November, during the southwest monsoon, to an average depth of five feet, owing to a rise of sealevel due to wind pressure, but constituting a barren and saline mud-flat during the remainder of the year. Over very flat areas facing shallow water bodies the seasonal direction and intensity of winds is thus seen to be an important factor.

A tabulation of the relations of depths to distance from shore for these various types of water bodies is given as follows:

Bottom Profiles established by Wave Action

Depths of water in feet

Type of water body	Distances from shore in miles				
	5	10	20	80	100
Stormy shelf seas..............	95	110	140	300	300
Stormy epeiric seas............	55	70	90	110	110
Quiet epeiric seas..............	35	50	70	90	90
Wide lagoons.....................	15	15	....	....	....
Playa seas........................	0 to 5	....	....	....	0 to 10

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[22] Joseph Barrell: Factors in the movements of the strand-line and their results in the Pleistocene and post-Pleistocene. Am. Jour. Sci., vol. xl, 1915, pp. 6, 7.

A good illustration of this limitation in depth is shown in the bathymetric contours of the Boston quadrangle, scale 1 : 1,000,000, U. S. Geological Survey. Sheet North K 19, International Map of the World.

[23] The writer is indebted to Doctor Bowman, director of the American Geographical Society, for data from the British Admiralty charts showing the details of the bottom of the Persian Gulf.

The depths of water given for these examples are probably somewhat above the average for their types, since the ancient examples were commonly shallow throughout and were generally not provided with adjacent reservoirs into which the excess of sediment could be readily swept. In such shallow bodies the wave action is damped down by the energy absorbed in stirring the bottom and can not become progressively greater with breadth of the water body. During storms choppy wave action and sediment churned up with water are the results. Upon the subsidence of the wind the sediment, even if mud, quickly settles in salt waters. Sediment must be slowly worked to the region of exit and escapes chiefly by combined wave and current action in time of storms. If the connections with the outer ocean are restricted, the water of the basin is shallower than for an open water body and a greater degree of bottom stirring will occur during storms. An average depth of several inches of sediment may thus be lifted from the bottom during the exceptional storms, to be quickly deposited during the following calm.

When evaporation exceeds rainfall in a nearly enclosed basin, such as the Mediterranean or Red Sea, the currents in general flow inward instead of outward. In extreme conditions of aridity sodium chloride is deposited, in less extreme conditions gypsum is the chemical precipitate; but even gypsum requires for its precipitation the concentration of present sea-water to 19 per cent of its original volume. Calcium and magnesium carbonates are insoluble, however, in sea-water concentrated one-half, or with lesser concentration where a lime mud has saturated a normal sea-water. In lime-depositing seas any tendency for evaporation to exceed rainfall in partly inclosed water bodies may thus supply more sediment to the bottom than is swept out through the restricted exits. The water body thus grows shallower until a seasonal change in wind may alternately cover and lay bear vast flats of lime muds. The importance of this action is indicated in the past by the abundance of intraformational conglomerates, mud-cracks, and occasionally rain-prints in certain limestones, as, for example, in the Precambrian dolomitic limestones of the Beltian system, in many Cambrian and Ordovician dolomitic limestones, and in the water limes of the Salina epoch in eastern North America. Thus have been developed the playa seas.

Where sediment is poured abundantly into an epeiric sea, the water is somewhat shallowed for a long distance. For example, soft mud is the chief material brought by the Tigris and Euphrates to the Persian Gulf and a depth of ten fathoms is reached only at a distance of 40 to 45 miles from the head of the gulf. The character of sediment on all bottoms tends to vary with depth, the sand being kept in the shallower water, but by far the most abundant sediment supplied by rivers is mud. Consequently, even shallow waters receiving such sediment show mud bottoms with fine sand as a subordinate constituent. The nature of the bottom of epeiric seas is consequently more dependent upon the breadth of water body, intensity of wind action, and character of sediment than upon the depth of water.

Schuchert, on the basis of the depth of wave action on the exposed shelves facing stormy oceans, has divided the seas into littoral seas and deep water pelitic seas, the littoral seas being less than 150 feet deep, the pelitic seas being from 150 to 600 feet in depth.[24] In view of the previous discussion it would seem that this, although applying to the shelf seas of the present, would be an overestimate for the epeiric seas of the previous eras. At times of world-wide equability of climate the temperature gradient between the latitudinal zones was weakened and the mean intensity of winds must apparently have been less, although the atmospheric conditions for the spread of tropic warmth to polar latitudes was at such times more efficient. In the epeiric seas, especially of the Paleozoic, the conditions of wave action should have approached those now found in shallow, partly land-locked bodies of water in the tropics. The prevailing wave bedding of the ancient deposits shows that the water was seldom deeper than wave-base. The general conditions of depth were therefore those shown in the previous tabulation for quiet epeiric seas, lagoons, and playa seas. It may be concluded that the ancient seas were typically not more than 100 feet in depth in their central parts and were often only a fraction of this depth over tens of thousands of square miles. Less frequently a rise of sealevel faster than sediment could fill in a basin would give depths of 200 or even 300 feet, but seldom deeper. Reviewing the prevailing conditions through geological time, it is seen that wave-base is a surface relatively parallel to sealevel and but little below it. During a stage of prolonged crustal quiet the wave-base is a surface below sealevel comparable to the fluviatile baselevel of the lands above sealevel, the former being depressed generally not more than 100 to 200 feet below the other, the one passing into the other through a slightly accentuated flexure constituting the shore and near-shore zone.

Thus baselevel may be used as a wide and inclusive term, applying both to land and sea. Nearly all sediment on the continental platforms, either terrestrial or marine, is deposited with respect to it. A further fundamental feature consists in the oscillation in short and long periods of this baselevel surface. On the land, in climates permitting fluviatile transportation of land waste, the local baselevel is the slope of the graded stream. This is subject to seasonal fluctuation. The depth and strength of current determines how close to the water surface the surface of sedimentation will approach. In the season of flood there is a deepening of the baselevel within the channel, as marked by the down-scouring. Over the floodplain a rise of baselevel accompanies the flood waters and deposition results. In the season of low water the action is reversed; then a silting up of the channel and a washing of detritus from the floodplain marks the seasonally lower baselevel and slackened current. For the sea-waters the factors leading to the oscillation of wave-base have already been discussed.

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[24] Pirsson and Schuchert: Text-book of Geology, 1915, pp. 490-493.

The sediment deposited at any one point is only a small fraction of that which is carried past. This small proportion which remains represents the rhythmic disturbance of a balanced condition. At a time of sinking baselevel, using this as synonymous with the surface of deposition, scouring will result, which means that a little more passes beyond the point than comes to it. At a time of rising baselevel the disturbance of the balance becomes additive and the geologic response is deposition.

The maintenance of shallow-water conditions during the accumulation of a formation means that there has been nearly always an excess of sediments above what was needed to maintain the surface at baselevel. This excess has been generally swept to the abyssal slopes of the continental platforms, building a continental terrace which has been the storage ground for the excess of waste. The deposits of the terrace have been, however, more commonly hidden from observation by being warped or faulted down toward ocean depths, rather than elevated, and in consequence exposed to erosion and observation.

In the sorting by wave action the coarser materials, as noted, tend to be kept on the landward side of the marine profile and therefore are deposited at wave-base; the suspended matter tends to be deposited in the deeper water farther from shore and partly below wave-base. Where there is an excess of sediment leading to deposition on the fore-set slopes of the continental terrace it must be to a large degree the finer material, giving the red and blue muds, mostly settling within a belt 100 miles wide beyond the outer edge of the shelf seas. A test, then, of the amount of sorting and deposition of sands in shallow water may be found by comparing the ratio of sandstones and shales as they occur in exposed geologic sections with the ratio to be expected from the erosion of the average igneous rock. Leith and Mead have made such a comparison. They find that an average of sections aggregating 520,000 feet, well distributed over North America, contains 46 per cent shale, 32½ per cent sandstone, and 21½ per cent limestone. An average of sections aggregating 188,000 feet, scattered through Eurasia, gives 49 per cent shales, 32½ per cent sandstone, and 18½ per cent limestone. The proportions which they calculate from the average chemical composition of igneous rocks should give 82 per cent shale, 12 per cent sandstone, and 6 per cent limestone.[25] Leith and Mead ascribe this discrepancy to the probability that many of the sediments consist of sandstones with undecomposed or unsorted material, including much shale, and further that many limestones are shaly.[26] It appears to Professor Schuchert and the writer, however, that this, although it may be a partial reason, can not be an adequate explanation. The chemical analyses of sediments should to a considerable degree include formations of these mixed compositions. An important factor in the explanation is the carrying of mud to the slopes of the ocean basins, because nearly always an excess of sediment has been supplied to the shallow seas beyond that which was required to keep their floors at wave-base. The mud deposits of these slopes are almost never exposed to observation. Thus this discrepancy between the observed and calculated proportions of sediments is in accord with the principles controlling sedimentation which are here emphasized.

The excess of limestones observed to occur on the continents, above their ratio to the total theoretical volume of shale, is also in line with the prevalent deposition of limestone under the control of wave-base. Calcium carbonate is abstracted from sea-water by organisms almost entirely in the zone of surface waters. Of this the part which is permanently lost to the continents is chiefly due to the accumulation of globigerina ooze on many parts of the ocean basins above 3,000 fathoms in depth. This ooze covers 40,000,000 square miles, 29 per cent of the entire ocean surface; but, as Murray and Renard have shown, the per cent of carbonate decreases with depth, so that the bulk of the permanent deposit is on the higher bottoms. The quantity of pelagic life per unit is greater in the waters of the shallow seas than in the central waters of the oceans. Add to this pelagic life the abundance of the lime-secreting bottom life of the sun-lit floors of the shallow seas, and it is seen why the limestones have been chiefly deposited on the continental platforms.

Thus, theory is in accord with observation in indicating that through geologic time deposition of marine sediments on the continental platforms has been in general controlled by wave-base, the terrestrial deposits by current-base. These controls have been subject to rhythmic oscillation in level—complex and superimposed oscillations, of longer and longer periods, years, decades, centuries, millenniums, and geologic periods in duration.

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[25] Leith and Mead: Metamorphic Geology, 1915, p. 60. By a typographical error the per cents stated in the book are in error for the limestones. The corrected figures given above are by Leith in response to an inquiry by the writer.

[26] Loc. cit., p. 68.

RATE OF SEDIMENTATION DETERMINED BY SUBSIDENCE

During the past century, although the prevalence in the sedimentary rocks of the marks of shallow water was observed, the importance of continental deposition was unappreciated; neither was there recognition of the control of baselevel over both erosion and deposition. It is very easy to transpose cause and effect where the two are essentially simultaneous in action and complex in their nature; and thus the older generations of geologists looked on the marks of shallow water, persistent through thousands of feet of strata, as the result of a delicate balance controlled by deposition, and not by depression. Every foot of sediment was supposed to be the cause, leading, as an effect, to a depression of the basin just one foot, with the result that a sea, always shallow, was supposed to have existed continuously throughout the Paleozoic. Even if such a marvelously delicate relation of subsidence produced by sedimentation were possible, they did not try to explain why the balanced condition should be attained at a level just below the surface of the sea. This necessary corollary is in itself sufficient to indicate that land conditions were in places confused with marine, and that the cause, a downwarping, was mistaken for the effect.

As another line of evidence, the writer has discussed elsewhere the features of the deltas of the Nile and Niger, built out on the slopes of the continental platform into the ocean basins. The extension of the land, as shown by the form of the deltas, into what was previously deep ocean indicates that the crust has there been able to sustain a burden equivalent to the weight of several thousand feet of rock extending over tens of thousands of square miles.[27] The stability of the land during baseleveling and the competence of the crust to support volcanoes are further evidence of its degree of stiffness and resistance to yielding under load. Beyond a certain limit, however, isostatic yielding is known to take place.

Although large rivers show a power to maintain their courses across growing mountain ranges, it is nevertheless true that the general drainage of a continent is away from the broadly upwarped areas and toward those which undergo downwarping. A relief map of the North American continent shows that the larger relief is determined at the present time by regional uplift and not by the dissection by river systems. The valleys are relatively shallow details carved in this relief, not the cause of it. This convergence of the larger drainage systems toward downwarping areas leads to the building of deltas selectively in regions of subsidence. If the land waste is moderate in amount, an epeiric sea rather than a delta occupies the downward region and is the reservoir of sediments. If, however, the downwarping is very profound, fore-set slopes and bottom-set deposits are built into an unfilled geosyncline or mediterranean deep.

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[27] Joseph Barrell: The strength of the earth's crust, part 1. Journal of Geology, vol. xxii, 1914, pp. 28-48.

On the surfaces of deltas or the floors of epeiric seas sedimentation records the rate of subsidence, not the rate nor amount of denudation. During stages of no subsidence there is no sedimentary record, except in fore-set or bottom-set beds usually on the margins of the ocean basins. During stages of slow subsidence a few feet of sediment may correspond in the top-set beds to a vast length of time. During stages of rapid subsidence in geosynclines the sediment has generally been supplied still more rapidly. As an illustration familiar to the writer, on the axis of the Appalachian geosyncline in Pennsylvania the floor subsided a maximum of 10,000 feet in the Upper Devonian. This did not result in a deepening of the water; but, on the contrary, the subaerial surface of the Catskill delta was actually built out across the axis of maximum subsidence and by the close of the Devonian had converted this whole section of the geosyncline into a land surface.[28] The work was continued in this region into the later Paleozoic periods, but there were times of interrupted record of unknown duration, as marked especially by the unconformity or disconformity at the base of the Pennsylvanian. It may be readily granted that this load of sediment, acting in the same direction as the forces initiating subsidence, would tend to continue it and carry it to greater depths; but without the sediments, deep water would almost surely have resulted, such as exists at present in the southern part of the Gulf of California, a geosyncline filled only at its northern end.

A relation appears to prevail frequently between the rate and height of uplift of a geanticline and rate and depth of depression of an associated geosyncline. When Appalachia supplied coarse and abundant waste it was deposited as thick formations in the parallel geosyncline. In the Ordovician a low rate of erosion is indicated by the dominance of limestones. The rate of supply of sediment was slow, but the water nevertheless remained shallow. Such a relation between parallel uplift and depression may be due to two general causes. Tangential pressure acting through a great depth of crust, if it bows up an arch on one side will tend to flex down the trough on the other; or the weight of a mountain system will tend isostatically to depress the crust in front of it; for example, the great weight of the Himalaya must tend to depress the rock floor of the geosyncline of the Indo-Gangetic floodplain in front of it over which it tends to be thrust. Whatever the cause, whether from horizontal thrust or from vertical load, there appears to be in times of high relief an accentuation of both uplift and depression. The rate of geanticlinal denudation and the rate of geosynclinal deposition are both at such times accelerated. At times of most pronounced uplift, however, the deposition is apt to be continental, the sediments excluding the sea. Elevation thus dominates over local subsidence, the excess of sediment is carried beyond, and the geosyncline represents a trap which retains only that amount of fill which is necessary in order that the rivers shall maintain their grade and carrying power across it.

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[28] Joseph Barrell: The Upper Devonian delta of the Appalachian geosyncline. Am. Jour. Sci., vol. xxxvi, 1913, pp. 429-472; vol. xxxvii, 1914, pp. 87-109, 225-253.

Notwithstanding these clear indications pointed out in the preceding paragraphs, nearly all arguments on the measurement of geologic time have rested more or less unconsciously on the assumption that the sediment would be deposited in a limited basin as fast as it was received. It has been conceived to be necessary merely to select the best rate of denudation and the relative areas of erosion fields and catchment basins in order to ascertain the rate of deposition. It is seen that in general the ratio of areas is but one factor of the problem, since usually only a part of the sediment has been deposited in the basin.

There were times, however, especially in the Paleozoic, when arenaceous and argillaceous deposits changed with distance from the shore into limestones. The limestones generally bear the marks of shallow-water origin. The material of the limestones must be looked on as derived from the ocean water and only in part from the same source as the clastic deposits. When the clastic materials change in this transitional manner into organic deposits it appears therefore that, unlike the cases previously discussed, the amount of land waste has been just about sufficient to fill the subsidence without a large balance to be carried farther beyond. Here, in the geosyncline, the rate of supply of sediment approaches the rate of deposition and a continuous record is more nearly approached.

The extreme case in slackness of sedimentation is that even in the geosyncline calcareous material may be the dominant deposit, as in the great Cambro-Ordovician limestones of the eastern United States, several thousand feet in maximum thickness. These limestones, however, show abundantly and recurrently the marks of shallow water and even exposure to the air, but the poverty of clastic material indicates that either the lands were very low and possibly somewhat distant, or that there was deeper water, with a bottom below wave-base, between the lime deposits and the land—a temporarily unfilled geosynclinal axis east of the present outcrops.

Although, theoretically, deposits of muds below wave-base settling from suspension in geosynclines should be expected to occur, yet they clearly are not a common type of sediments. They are the only deposits, however, from which a continuous record of deposition may be read, and should be sought from this point of view.

The discussion of this topic has thus far turned on the factors controlling the rate of sedimentation. In the light of this discussion, how does the present rate compare with the rates in the past? There are two world-wide features characteristic of the present which determine the answer: One is the present high degree of relief of the earth's surface, as shown by the contrast of the present and past curves of relief as illustrated by figure 3 and discussed in Part I; the other is the direction of the last movement of sealevel.

To take up these in order: The present high relief is a feature which means the rapid downwarping of many catchment areas for sediment during the Neocene and Pleistocene. Very thick formations have been made in a short geological time. A few are upturned and exposed, as in the younger Tertiary formations, which make foothill ranges; for example, the Siwalik formations of India, 14,000 feet in thickness. Other sites of sedimentation, as intermontane basins, are in many cases still somewhat below grade, maintained so by subsidence, and are being rapidly built up. Where no catchment basin is crossed by the rivers flowing from mountains, a large amount of land waste is rapidly supplied to the sea, building out deltas or adding to the continental platforms as a submarine terrace of construction.

To turn to the other factor—the direction of the last movement of the sealevel; the evidence of the shorelines shows that the last stage has for most shores been one of submergence. River mouths are drowned and transformed into harbors and estuaries; the sea is cutting vigorously at the headlands of embayed shores. The motion has been more or less intermittent and there is little evidence that it is now going forward. The evidence around the northwestern shores of Europe indicates, however, that there the last movement of submergence occurred not more than 5,000 or 6,000 years ago. The generality of recent submergence as the latest phase suggests that it is a movement of sealevel. At a slightly earlier time, the retreat of the great glaciers from the last Pleistocene advance has added between 100 and 200 feet of water to the sea and would appear to be an important factor in the general submergence of coral islands to a depth of 20 to 30 fathoms.

These movements have resulted in the recent depression of the surfaces of sedimentation in deltas and the bordering seas and a corresponding acceleration in upbuilding. Estuaries and tidal bays such as the Persian Gulf, the Adriatic and Yellow seas, are being filled; coral growth has received a great expansion; for the time being the rate of sedimentation approaches the rate of supply of waste. The lack of recognition of the variable nature of these conditions has permitted geologic thought to project them backward through past time as the normal procedure. It is seen, however, that before geologic retrospection can be sound it must recognize in the principles of perspective the markedly cyclic or rhythmic nature of geologic activities, both in denudation and in deposition, and the acceleration of both these processes at the present time, owing to the concurrence of several controlling factors.

PROGRESSIVE TILTING COMBINED WITH RHYTHMIC OSCILLATION OF BASELEVEL

Sediments are deposited either in geosynclines, as prisms thickening toward the axis, or as thinner, lenslike formations in shallow downwarped basins, or on the continental shelves in the form of wedges thickening seaward. In any case room for further sediment is made by downwarping. On the slope of the depressed area this is expressed as a tilting of the floor about an axis. On the landward side there is uplift and erosion; on the seaward side depression and deposition. This tilting of the floor about an axis is, then, a general phenomenon of diastrophic origin connected with sedimentation and is expressed by the thinning down and dropping out of stratigraphic members when followed toward the limits of the formation.

The tilting, like all other crust movements, is discontinuous. Pulses of erosion occur on the landward side. On the seaward side of the axis, by depression of the baselevel, room is made more or less simultaneously for more sediment. These rhythmic pulses, provided that sedimentation is controlled by baselevel, will result in divisions in the stratigraphic series separated by breaks, visible or invisible.

At the same time that the floor is being warped, there are, owing to other causes, rhythmic elevations and depressions in the baselevel without tilting. For example, the rhythm of the seasons causes river action and wave action to fluctuate in level; the extreme conditions of exceptional years are especially potent in upbuilding or in down-scour. Slow changes in sealevel, hundreds or, more usually, thousands of years in length, form pulsations of a higher order which affect marine and delta deposits. Climatic fluctuations of short and long periods cause variations in the supply of sediment and the carrying power of rivers. These oscillatory rhythms are combined with the discontinuous movements of tilting which are not oscillatory, but irregular and progressive in one direction. In studying the stratigraphic consequences of the combination of the two, the tilting may be regarded as progressive—that is, as continuing longer than the other rhythms—and the latter as producing a parallel rising and falling of the baselevel. In such rise and fall the motion at the turning points is for most kinds of motions very slow, as in the tidal ebb and flow, or may be even arrested until sufficient force has become accumulated. This combination of progressive tilting with

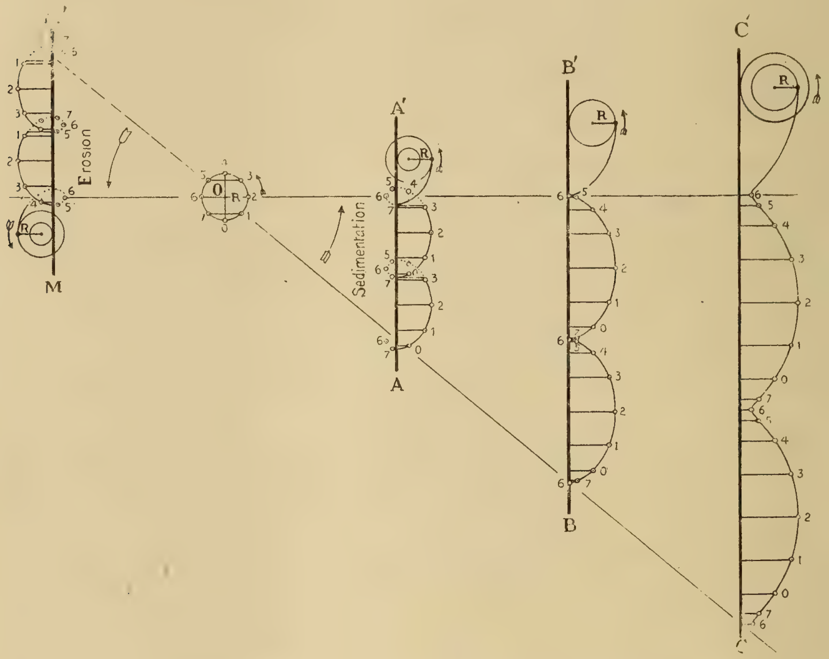

Figure 4.—*Diagram postulating a progressive Tilting of the Crust, combined with a rhythmic Elevation and Depression of Baselevel*

This diagram illustrates a variable rate of sedimentation dependent on baselevel and distance from axis of tilting. R = radius of oscillation. 0, 1, 2, 3, etcetera, represent the position of baselevel at equal time intervals.

oscillatory rise and fall of baselevel must be very general in its applications and figure 4 is drawn to illustrate its results.

In explanation of this figure it will be noted that the tilting or rotation indicated about the axis through 0 results in sedimentation on the right, in erosion on the left. The oscillatory rise and fall, for the sake of simplicity, are assumed to be of a harmonic nature, as in the rise and fall of a point on a wheel which revolves on a fixed shaft. The successive stages during one cycle are shown at 0 by the levels 1, 2, 3, etcetera. But on the line B B′ the progressive rise in baselevel due to tilting is the same during one oscillation as the circumference of the circle of oscillation. The combined motion gives a cycloid, the path of a point on the circumference of a rolling wheel. The successive levels 1, 2, 3, etcetera, at equal time intervals show no scouring, but a marked slowing up of deposition between stages 4 and 0 and a momentary cessation at 6. Farther from the axis, as at C C′, there is continuous rise of baselevel and accompanying deposition, but at unequal rates. At a great distance from the axis the rate approaches uniformity.

Between B B′ and the axis 0 the curve is a trochoid. In this section there is downscouring and loss of record through a part of the cycle of oscillation. At A A′, half way between B B′ and the axis 0, there is a sedimentary record of only one-half the time. At 0 deposition and erosion alternate and balance. At M M′ erosion dominates, but during one-half of the time at this place there is sedimentation.

To apply this diagram to the geologic record: Most regions of sedimentation have been subject to alternate fill and scour, with a balance in favor of the fill, representing the section of the curve between 0 and B B′. Where formations thin out, only occasional thin beds are preserved. Many beds are missing and the record is very imperfect. On the other hand, on the foreset beds of deltas, on lake bottoms, occasionally on the rapidly subsiding axes of geosynclines, and generally on the slopes of the continental platforms, the conditions approach those shown on C C′ and a complete sedimentary record is developed. The diagram is valuable in visualizing the incomplete nature of the sedimentary column in most regions and in emphasizing the large time values of the breaks in deposition, a part of the lost interval being represented by beds which are later removed. Here only one rhythm is shown. In nature the record will ordinarily be more complicated, minor oscillations being superimposed on larger. During the passage of a single rhythm there would be in effect a to and fro migration of the transition line which separates erosion from deposition between B B′ and a point equally distant on the other side of 0.

The Atlantic coastal plain of the United States may be cited as an illustration of these principles, valuable furthermore in showing how nature departs from the simplicity of a diagram. In the Jurassic the transition line between erosion and sedimentation was southeast of the present shore and erosion prevailed on all the surface now open to observation. Near the end of the Jurassic or beginning of the Comanche, a pronounced tilting took place, accompanied by a northwesterly migration of the axis inland to somewhat beyond the present edge of the coastal plain. As a consequence, the Patuxent formation, of fluviatile origin, was laid down. Then emergence occurred; that is, the axis migrated eastward, and erosion took place to some extent. Then another rhythm again depressed this region, elevated the baselevel, and the Arundel formation was deposited. Here the deposition was brief, as the formation is found within shallow valleys which had been cut in the Patuxent. Following diastrophic rhythms resulted in the Patapsco, the Raritan, and the Magothy. The formations now become marine and the Matawan and Monmouth follow. Between each formation is an unconformity which near their landward margins probably represents much more than half of the total time. Besides the diastrophic oscillation superimposed on the tilting, the stratification of the sediments, as shown in the variegated beds, shows many minor rhythms, doubtless in part climatic. During the Cretaceous the shore migrated inland, uplift slackened, and the resulting waste was less. The sedimentation was now wholly marine and the record for a time is probably more nearly complete than it was during the Comanche, although the thickness of sediment is less. Possibly the greensands of the Cretaceous represent for a time a continuous record, for these are now found to be developed in quiet waters near the limits of wave action on the outer parts of the continental shelf. The Tertiary formations show the continuation of a history of oscillations similar to those shown in the Comanche and Cretaceous, long intervals of sea retreat alternating with advances. Throughout all this time there seems to have been a progression in tilting, doubtless irregular and spasmodic, but irreversible, combined with complex vertical oscillation of the baselevel in longer and shorter rhythms.

Let this record on the shore of a continent be compared with the record as made in a geosyncline within the continent as seen in that of the Appalachian trough. The latter throughout the Paleozoic received sediments from the eastward from the land of Appalachia. The maximum thickness was perhaps 40,000 feet, mostly clastic deposits, but with thick limestone formations intercalated. The sandstones and shales do not represent continuous deposition where they are thickest, for there was much clastic sediment carried beyond the axis of the geosyncline. The surface was therefore kept near baselevel, and the minor rhythms must have exercised a scouring action during a part of their cycle. The limestones most conspicuously show the absence of a continuous record. They are shallow-water deposits; the successive beds are often in great contrast, and innumerable laminæ show, in longer and shorter cycles, oscillation of conditions.

But the southeastern side of this trough of sediments has been uplifted and eroded, with the result that the thickest outcrops of the several formations are commonly the easternmost. If the record was discontinuous in this region of maximum thickness, it was presumably more discontinuous in the portions to the southeastward which are now destroyed. The deposits of a continental shelf, if traced outward far enough, must begin to show a continuous record. Those of a geosyncline, even one containing a maximum depth of 6 to 8 miles of sediments, may be almost throughout a discontinuous record. The thickest formations, although rapidly accumulated, are in most cases of such a nature that a continuous deposition can not by any means be granted. The coarseness of such very thick formations is no criterion of continuity; in fact, it favors the opposite interpretation. The coarseness measures the strength of the streams or waves. Where these are strong, there must, as argued before, be much material carried beyond that point; and, corresponding to rhythmic ebb and flood of carrying force, there must have been alternate fill and scour.

If this interpretation be true, it is seen how unjustified is a procedure which assumes a certain rate of deposition for the thickest formations—a foot per century, as Sollas has taken, and multiplies this by the thickness to determine the time of deposition, making no allowance for the longer and shorter down-scouring phases.

A careful study of the stratigraphic record has brought to light many breaks in deposition within series of similar beds which lie on each other in parallel fashion. These breaks are recognized by noting a sudden change in the fauna or flora at a certain plane, or a sudden change in the nature of the sediments, especially where a coarser layer lies on one of finer grain. The time interval may be great, as where the totally distinct fauna of a later period rests on beds containing the earlier fauna; or the faunal change may be slight, as where in one bed of limestone some species are the same as in the bed below, but others are replaced by new species. Such a plane representing a lost interval has been named by Grabau a disconformity.[29] With the recognition of the importance and number of such planes, the word has become well established in geological literature. Many lost intervals must exist, however, in deposition which are of less duration than those which are detected by marked biotic or physical change. The arguments in the present article point out their large aggregate time value and the generality of their occurrence, owing to the rhythmic character of sedimentation. They must be recognized from the physical conditions of deposition, especially by sharp surfaces separating beds, or by sudden changes in the nature of the sedimentary rhythm.

The term disconformity has come to refer to a well defined hiatus of larger value and essentially due to diastrophism in elevating the land or depressing the ocean level, although for lack of a separate term these minor breaks would also at present be included as minor disconformities. The distinctness of the two classes of lost intervals and the emphasis placed here on the class of smaller pauses, due largely to oscillations in the intensity of climatic factors, seem to justify the erection of a new term and the restriction of the class of disconformities to those breaks which have a large enough value to be recognized by change in fossils or marked contrast in sedimentation. A suitable name appears to be *diastem,* the word meaning a space or interval. It was formerly used in music as signifying an interval. The Latin form, *diastema,* is now used in zoology with the special meaning of a vacant space, or gap, between teeth in a jaw.

A disconformity marks a period of time which is represented in some other region by a deposit of formation value. A diastem is a break represented in other regions, often within the same formation, by a bed or series of beds. A disconformity is theoretically traceable over a broad area. For deposits of epeiric seas it means ordinarily a movement sufficient to more or less completely drain the sea-water from the continent. A diastem does not imply the draining of a shallow sea, but rather a shorter or longer downward oscillation of wave-base. The two classes of breaks, although typically distinct, must grade into each other. The assignment of a break to one or the other category must not depend on a doubtfully assigned cause, but must rest on the observable field evidence. Therefore the discrimination should rest for disconformities on breadth of occurrence and faunal or floral change, for diastems on breaks in continuity of lesser areal importance, of greater number, and not characterized by permanent faunal or floral change. The presence of diastems makes for a slow rate of accumulation of a formation, associated with a more rapid rate of accumulation of the individual beds.

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[29] A. W. Grabau: Principles of Stratigraphy, 1913, pp. 821-826.

NATURE OF STRATIGRAPHIC RECORD RESULTING FROM COMPOSITE RHYTHMS

The making of a sedimentary series is conditioned on an oscillating but progressive rise of baselevel. Nature is not so even in her course as to give truly harmonic motion, but in a theoretical discussion that may be assumed as the simplest form, and it will be shown that it does not exaggerate the amount of time which is represented by the intervals. In this type of oscillation the vertical motion slows gradually to nothing at the limits and is most rapid at the middle of the cycle. But nature pulsates with many rhythms, small and large, fast and slow. Their combination gives a varied curve which, if the rhythms are incommensurable in period, may never recur in quite the same combination. How will such composite rhythms affect the stratigraphic record? In figure 4 a diagram was given which compared for various locations the continuity of the record due to a simple rhythm combined with continuous warping. Here another aspect is considered. It is represented by a diagram which will serve to visualize the nature of the stratigraphic record for one place, as dependent on the relations of period and amplitude of the several components of composite rhythms. Figure 5 is drawn for that purpose. In this diagram time is measured from left to right and the rise of baselevel is measured in the vertical direction. The curve A A represents a long term rise of baselevel, beginning slowly, gaining in rate, and then slowly ceasing. This is a portion of a harmonic curve, but for this fundamental curve it could not continue except with respect to a sloping axis of coordinates, as otherwise the following downward sinking would destroy the entire series made during the previous rise.

Such a general rise of baselevel will be accomplished by diastrophic oscillations. In the Paleozoic these larger oscillations are indicated by the coming and going of the epeiric seas or the shifting of their areas. They were usually so slow that erosion and sedimentation kept pace with them and widely extended deposits were laid down, alternating with disconformities.

In the Pleistocene there has been by contrast a general sinking of baselevel, shown by the emergence of the land, but the movement here also has been strongly oscillatory, as shown by the drowned river valleys, and above the sea level, by the several Pleistocene formations, partly of alluvial and estuarine nature, partly marine, which skirt the margin of the continent. In Maryland the late Pliocene Lafayette deposits were uplifted and dissected. Then submergence took place to a maximum of 220 feet above present sealevel and the early Pleistocene Sunderland was deposited. Uplift caused dissection as before, and then another submergence to 100 feet led to the deposition of the middle Pleistocene Wicomico. This in turn was uplifted and dissected. Finally, the late Pleistocene Talbot formation was laid down up to 40 feet above present sealevel. In these Pleistocene deposits the aggregate progressive movement of baselevel was in a contrary direction to that which leads to the permanent preservation of sediments. They have, furthermore, been geologically rapid, but the nature of the oscillations is nevertheless illustrative of the habit of diastrophism, clear to us because of the recency in time.

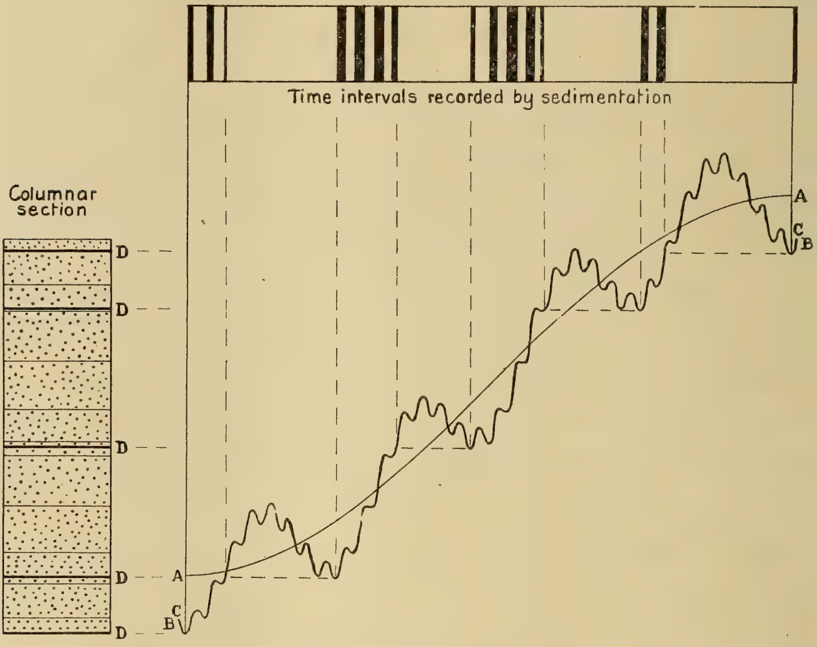

FIGURE 5.—*Sedimentary Record made by harmonic Oscillations in Baselevel*

A-A. Primary curve of rising baselevel.
B-B. Diastrophic oscillations, giving disconformities D-D.
C-C. Minor oscillations, exaggerated and simplified, due largely to climatic rhythms. Equation of curve C-C: $y = \sin x - .25 \cos 8x - .05 \cos 64x$.

In times of slow movements of baselevel the numerous smaller rhythms, some of which are climatic in their origin, are able to take effect in the planation of unconsolidated sediments. These frequent smaller oscillations give a crenulation to that sinusoidal curve which measures the progress of diastrophism. In figure 5 the curve C-C shows the summation of such effects for three combined rhythms, such as have been discussed, of successively smaller amplitude and shorter period.

On the left is the columnar section of the strata which result from these combined oscillations. The light lines of separation are the bedding planes, or diastems, and in the curve as here drawn represent lost time intervals about equal to that recorded by the beds. The heavy horizontal lines are disconformities due to cessation of sedimentation and downscouring during the recurrent longer stages of sinking baselevel. On the curve as here drawn they represent considerably longer times than the intervening formations. Lost intervals of more than half the time necessarily occur for harmonic oscillations, if the trough of a secondary rhythm is lower than its preceding crest; in other words, if the slope of the limb of the secondary rhythm in descending phase is steeper than the slope of the primary rhythm in opposite phase. On the other hand, if the minor rhythms have very long period and low amplitude they will not interrupt the continuity of sedimentation on the ascending limb of the next higher rhythm, but will cause only variations of rate. There will be bedding, but no diastems.

The evidence of recent climatic and crustal movements indicates that the changes are relatively rapid, separated by intervals of quiet. The combined curve would differ from the simple harmonic form by showing longer flats and sharper vertical movements. Where sedimentation is closely controlled by baselevel it would mean a necessary discontinuity, or diastem, involved in each rhythm. The assumed harmonic motion, by giving gradual slopes to the curves, is apparently more favorable for giving continuity of record than are the more abrupt changes of nature. In figure 5 the columnar section looks not unlike those found in nature; yet only one-sixth of the time is recorded in it, as shown by the black bars above the curve. The actual material existence of the strata is so much more impressive than the division planes between them that this diagram is necessary to show how for this case the strata give a record for only a small fraction of the time.

The rapidly subsiding center of a geosyncline would correspond to a steepening of the curve A A and a larger proportion of the time would be recorded than on its landward margin. Where the diastrophic oscillations are large as compared to the progressive change of baselevel, as near the margin of sedimentation, or in places of but little progressive submergence, the record is, on the other hand, very discontinuous. Smaller oscillations are in part of a diastrophic nature and are compounded of changes in the level of sea and land. Many small oscillations and some of even larger magnitude are, however, dependent upon climatic change.

The growth of glaciers abstracts water from the sea and locally depresses the land, but a more general effect through geologic time is dependent on changing river grades. In times of lessened water and increased burden, they steepen; under opposite conditions, they flatten. Where the rivers flow 100 miles or more from mountains to the regions of deposition a change of baselevel amounting even to some hundreds of feet may result. This affects especially the continental deposits, but unbalances also the ratio of supply of waste to the carrying and eroding power of the sea.[30] Such an oscillation in river grade appears to be an essential factor in the interpretation of the upper Paleozoic formations of the Appalachian geosyncline and must apply to certain other regions also.

The curve, to correspond to nature, should be imagined as less regular and with more orders of rhythms. For regions where the sediment carried past to other localities is large compared to that which comes to rest at that locality, the record becomes very discontinuous. As a result of introducing further rhythms, in those places the black bars in the upper part of the figure which show the time intervals recorded by sedimentation should be in reality broken into gridirons by smaller cycles, cutting out by diastems more and more of the record until the whole comes somewhat to resemble the Fraunhofer lines in the solar spectrum.

A fundamental conception connected with composite rhythms is that a long time interval may be represented by a short columnar section, and yet the individual beds may be deposited rapidly. In coal measures, tree trunks may be preserved in erect attitude, showing burial before decay. In marine deposits, sponges and coral colonies are in certain beds found smothered in mud. Ammonite shells were partially or wholly buried before they could be destroyed. Such burials may have been due to single unusual storms, recurrently scouring sediment from one locality to deposit it in another. At the most, but a few years could have been occupied in the burial. These features show rates of accumulation so rapid that even the advocates of very short geological time would have to admit for such instances recurrent deposition with lost intervals between. But having once admitted the principle, the basis is destroyed for estimating the time of accumulation of the whole formation by means of an assumed rate of continuous denudation and corresponding sedimentation.

ILLUSTRATIONS OF RHYTHMS IN SEDIMENTATION

In advocating a view that sedimentation on the continental platforms in either marine or terrestrial deposits is more often discontinuous than continuous, on both a small and large scale, some discussion should be added as to what are conceived to be the stratigraphic marks of such discontinuity.

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[30] Joseph Barrell: Relations between climate and terrestrial deposits. Journal of Geology, vol. xvi, 1908, pp. 159-190, 255-295, 363-384. The Upper Devonian delta of the Appalachian geosyncline. American Journal of Science, vol. xxxvii, 1914, pp. 239-243.

Leaving aside the significance of angular unconformities as not needing amplification, we may pass to disconformities. These, as previously noted, are not recognized by any structural discordance, but are marked by change of faunas and represent lost intervals of greater or lesser duration; thus they may represent the passage of geologic periods, or they may exist between formations in the same period. Recognition of the large number and importance of disconformities has grown within the past decade, but in their nature, like faults, they must be far more numerous than the evidence can demonstrate. Careful study of the Mesozoic and Cenozoic formations of the Atlantic coastal plain has shown that unconformities lie between nearly every formation. In the Patuxent folio, Maryland, twelve post-Triassic-pre-Pleistocene formations are listed. Of the eleven surfaces of separation between them, nine are given as unconformities. But formations which are not separated by unconformities, as well as the members within a formation, may or may not possess continuity of sedimentation through the large cycle which they represent. If a transition zone exists between two unlike deposits, the suggestion given is one of continuous deposition. This is more probable if the transition is from coarse below to fine above. On the other hand, if there is a sharp contrast, a break in continuity is suggested, and this is more probable if the contrast is from fine below to coarse above.

Passing to the smaller rhythms which characterize beds rather than members of formations, two beds which grade from coarse below to fine above are presumably continuous, but each such pair may be separated from adjacent pairs by a stage of scour or non-deposition, since each coarse bed must lie in turn on one of finer texture. It would be unsafe, however, to use it as an absolute criterion of minor discontinuity, as it is quite possible for sand to be washed over mud-beds without necessarily producing a down-scour. Illustrations of the nature of discontinuity may be given from several types of beds. The first will be for dunes.

Sandstones of terrestrial origin may be produced by wind. The sand travels in the form of dunes. As these slowly march across a tract of accumulation, a region to which more sand is brought than is taken away, the basal part of each dune may be left behind and buried under some following dune. The long sweeping curves of the cross-bedding are planed off and the angular unconformities in cross-bedding indicate a lack of continuity of record with the sand above, giving a diastem. According to shifts in the intensity and directions of the wind, more sand may be taken away than is brought to the region, down-scour may take the place of upbuilding for shorter or longer periods, and the break, or diastem, between two similar beds represents an unknown time interval. The crescent form of dunes brings in further local complexities, but these may be eliminated in this discussion. The subject lends itself to diagrammatic illustration which brings out impressively the relatively large time value of the lost intervals represented by the division planes between beds.

In figure 6 are illustrated the principles which enter into the building and marching of dunes, but the same reasoning applies in a general manner to all sedimentation where there is alternate fill and scour. The wind is shown blowing from left to right. It rolls and jumps the sand particles up the gentle back slope of the dune and at the crest meets a return eddy. When the wind is strong the sand is seen suspended in the air just to the lee of the crest and the dune is said to smoke. At the top of the lee slope the sand at the crest is kept by the return eddy on a slope of about 30 degrees or a little more—the angle of repose. The curvature of the wind currents gives broad sweeping surfaces, passing from the lee slope up the flat back of the next dune to its crest. The dune grows by adding successive beds to the lee side, and these are progressively cut out by the scour on the windward side. Where there is a progressive accumulation the down-scour does not cut on the average quite to the base of the dune.

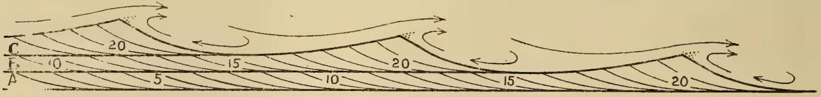

FIGURE 6.—*Diagrammatic Cross-section to illustrate Time Values of true bedding Surfaces between Beds of false-bedded Dune Sands*

In the diagram the wave length of the dune is divided into eight stages. A21, B21, C21 are laminæ of the same age; but lamina C21 lies above B13 and this in turn above A5. The time value of the breaks represented by the planes of separation is given by the time which is taken for a dune to advance one wave length compared to the thickness of the beds spared by the down-scour. Thus, in a vertical section just back of the left-hand dune, time intervals 3, 4; 11, 12; 19, 20 are represented by sediments; the intervening times are represented by the breaks.

The dunes of the great deserts are often several hundred feet in height. As seen in plan, the typical form is the crescentic barchane, the wings of which slope downward. The wind shifts in direction, and different years are marked by notably different maximum intensities. The great bulk of sand movement is accomplished during relatively brief periods of intense winds. These factors, as previously noted, make the actual structures in nature far more complex than the simple diagram. Nevertheless, the average or aggregate effect is well represented.

If the sand swept by wind from the source in the stony desert or hamada, or brought by streams from mountains, is accumulating uniformly over a distance of a hundred miles, then over the first mile only 1 per cent will remain and 99 per cent will be carried beyond. As equable deposition can not be postulated, there will be many times when scour rather than deposition takes place in the first mile. The exceptional winds of a single year may scour down to the layers deposited in a previous century and a few following years of slack winds may more than fill in all of the scour. Thus it would be a common feature for C of the diagram to come to lie below B or A, or even below far lower beds. If C should cut down below B, it would bring lamina C21 into contact with A 3, 4, or 5.

It is seen that the average length of the time break, or diastem, between beds depends on the ratio of the volume of material of that kind which is carried beyond to the volume which is deposited in the locality of the bed, but on account of the lack of uniformity which exists in Nature the actual value of an individual break might range from nothing to many times the average. The conclusion of far-reaching importance is that coarse detritus and rapid accumulation of individual beds is no criterion of rapid accumulation of the formation as a whole. This needs to be emphasized because the natural tendency, without analysis of the problem, is for geologists to assume the contrary to be true.

Looking at the farther side of the region of deposition, it is seen that during the maxima of transporting power there is only deposition and no removal of material; but at times when the wind is less intense, there is no transportation of material of this grade of coarseness to such a region. Thus it may be taken as a general proposition that the coarser the waste and the more rapid the accumulation of individual beds, the longer, *relatively,* are the times of non-deposition. Furthermore, it is seen that on the side of the formation toward the source the break, or diastem, is due to an accentuation of the carrying forces. On the side away from the source the lack of deposit is due to the alternating quiescence in transportation. The diastems in one locality are represented by beds in another locality in the same formation. Each section may show a high degree of discontinuity, and yet if various sections could be pieced together a more or less complete record might be attained.

The rate of accumulation of conglomerate and sandstone formations, as well as that of the individual sand beds, may be on the average more rapid than that of argillaceous formations, and these in turn possess a higher rate than that of limestone formations, but these rates of accumulation are due to the relative rapidity of crust movements generally implied by the coarser waste as compared to the finer, not because the individual beds of sandstone or mudstone are individually more rapidly deposited.

In river deposits the migration of the channel produces scour *into* the floodplain deposits, but the natural levees are laid down *on* them. Thus, in alluvial formations there may be both continuous and discontinuous deposition. Shifts in the regimen of the stream due to variations between the supply of waste and the amount of water are more important. Climatic pulsations thus affect the river grades, and stages of scouring alternate with those of upbuilding. The high plains of the western United States have in this manner suffered alternate dissection and partial rebuilding on a large scale recurrently through the Pleistocene. This oscillation in fluvial transportation is apparently an important factor leading to the division of clastic formations into members, even where the final deposition of the sediment is on the floor of the epeiric sea.

S. H. Knight, in his study of the "Origin and Age of the Red Beds of Southeastern Wyoming,"[31] has shown that certain beds have been cemented; then eroded, and by a return to aggradation, great residual boulders were reburied *in situ* in younger beds of enveloping sediments of the same formation, thus giving rise to a peculiar type of interformational conglomerate.

Farther from the source of sediments, on the deltas of rivers, or in front of the delta on the floor of the shallow sea, the possibility of deposition depends more closely on subsidence. The river builds up quickly after each stage of down-sinking, and then, after grade is reached, carries its sediment farther out. It must wait for further subsidence before it can make more than thin deposits on the inland portion of the delta.

In limestone formations discontinuity of sedimentation is indicated by recurrent exposure to the air, but also by several other features. The cementation of lime muds is favored by supersaturation of the waters; solution, on the other hand, results from freshening and undersaturation. The wearing down of shells and the transportation of the lime mud elsewhere may retard or even stop the local accumulation. The alternate freshening and saturation of the waters tends to carry away the calcium carbonate and concentrate the less soluble magnesium into beds of dolomitic limestone. Thus there may be continuous or discontinuous accumulation in limestones, but the dominant features of most of these formations suggest that sedimentation was markedly discontinuous from bed to bed.

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[31] Presented orally to the Geological Society of America December 29, 1916.

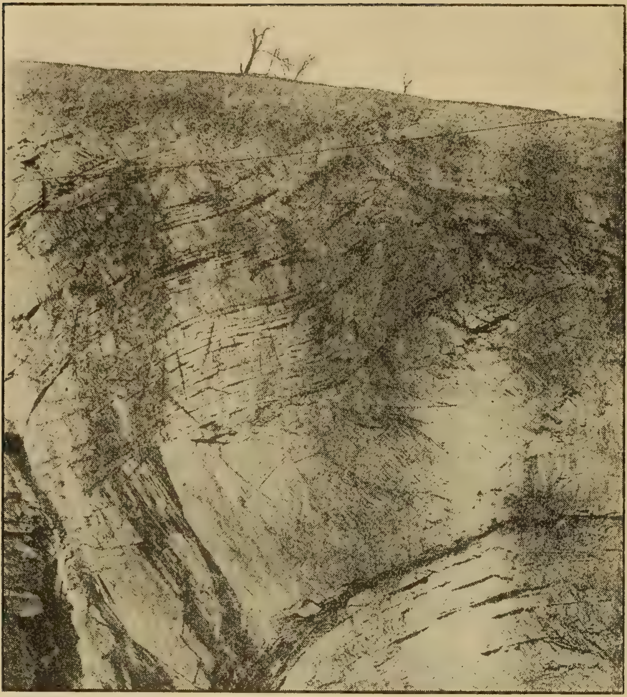

FIGURE 1.—BEDDING IN SLATE QUARRY, UPPER ORDOVICIAN, SLATEDALE, PENNSYLVANIA
Photograph by H. S. Palmer, 1913

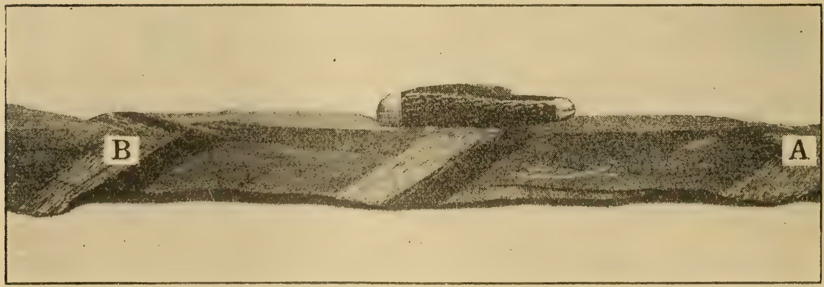

FIGURE 2.—RIBBONED SLATE, UPPER ORDOVICIAN, SLATEDALE, PENNSYLVANIA
The ribbons have a dual division, consisting of carbonaceous mud below and fine-grained sand above, emphasized by retouching the photograph

UPPER ORDOVICIAN SLATE OF PENNSYLVANIA

Turning to marine mudstones, it would seem that here are the most favorable conditions for a continuous record. They seem well adapted, especially where markedly alternating with beds of lime or silt, to give a basis for the analysis of rhythms.

An instructive illustration of what is probably in some beds a continuous record and in other beds a record not greatly discontinuous is found in the Martinsburg or Hudson River slates. The writer has studied them especially in eastern Pennsylvania, where the commercial value of certain beds has resulted in extensive quarrying and numerous exposures. The formation is here in considerable part a silt rock. This facies, where studied in the neighborhood of the Lehigh River, is divided into beds from several inches to several feet in thickness, constituting a ribboned slate. An illustration showing this feature is given in plate 43, figure 1. In a single exposure the rhythm in bedding tends to great regularity. Through most of the formation the ribbons are reduced to mere parting planes between beds of silty character. In places thicker beds may be almost uniform in texture, but have thin bands of lighter color running through them which appear to be due to a slightly lower content of carbonaceous mud. Such faint color bands may not destroy the value of the slate. In some localities these bands of slightly lighter color alternate with a very regular spacing with bands which vary in the other direction, containing softer and blacker material. All these varieties of divisions in bedding are thus seen to be due to related causes of regular recurrence. Turning to the notably ribboned slates, we may find in them the key to the significance of the bedding. The ribbons often consist of a band of soft black mud-rock overlain by a band of nearly clean sand. The mixture of the two would appear to give the normal composition shown in the intervening beds. This sequence is illustrated in plate 43, figure 2.

The layer of sand is often subdivided into laminæ and occasionally shows ripple-mark. Kindle has shown by experiment that in a silt deposited after stirring up in fresh water the coarser particles are deposited first, whereas in salt water the coagulation into nuclei is such that the slimes are deposited first, and the very fine sand follows.[32] These ribboned slates indicate, consequently, that at recurring intervals the bottom of a shallow Ordovician sea was stirred up by waves of unusual intensity. On the dying down of the wave action the sediment which was held in the water at that place settled, making the ribbon of this character. It can not be assumed that the recurrent strong wave action churned up the sediment without carrying any away. The width of the ribbon represents merely what settled from the water on the subsidence of the storm. During the progress of the storm, sediment was being scoured out and worked to localities of deeper and quieter water. The development of the bedding planes in this slate and their expansion into ribbons represent, then, a region and a depth where waves gently agitated the bottom, sweeping material along and spreading it out in the quieter waters. Rhythmic intensification of this action resulted in an alternation of fill and scour in which the surface of sedimentation was raised and depressed by changing intensity of wave action and maintained throughout a marked parallelism distinctive from current action.

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[32] E. M. Kindle: Diagnostic characteristics of marine clastics. Paper presented to the Geological Society of America December 29, 1916.

Certain inductions having wide application to beds of marine silts may be drawn from this clear example. The regularity in the succession of the beds and the grouping of these beds into sequences shows a combination of climatic rhythms marked by varying intensity of storms. The sediment was deposited in close accord with wave-base, and the downscouring probably did not cut out more than half of each deposited bed, since otherwise the remainders would not form such a regular series. After each culmination of intensity continuous deposition, so far as this cycle is concerned, seems to have occurred, giving rise to the following bed with a definite and constant mixture of mud and fine sand. Considering the fine-grained character of the sediment, the wide area of the formation, and the abundance of carbon, the sediment must have been deposited slowly. The thickness of the beds, ranging from several inches to several feet, indicates, then, a rhythm far too long to be regarded as seasonal. It can not be less than decades or centuries in length. The land lay to the eastward and was presumably low. The denudation rate was consequently slow, and therefore, as a maximum limit, the cycle may represent some thousands of years. The amount of variation in wave intensity to give this rhythm was moderate. Thus we reach the conclusion that the climate was more uniform than at present, but was affected by regular oscillations comparable to the Brückner cycle of 35 years, but more probably of longer period. Such a regularity in climatic rhythm suggests as a cause fluctuations in solar energy. In the strata of such ancient formations is locked up, not only a history of the planet. but also the history of the sun as a variable star.

Some further illustrations of the variety of rhythms, especially those showing in disconformities and diastems, should be given. The first of these, taken up in sequence of age, is a view of a series of cryptozoan beds from the Lower Ordovician (see plate 44, figure 1, photograph of an exposure near Allentown, Pennsylvania). The cryptozoan layers show white

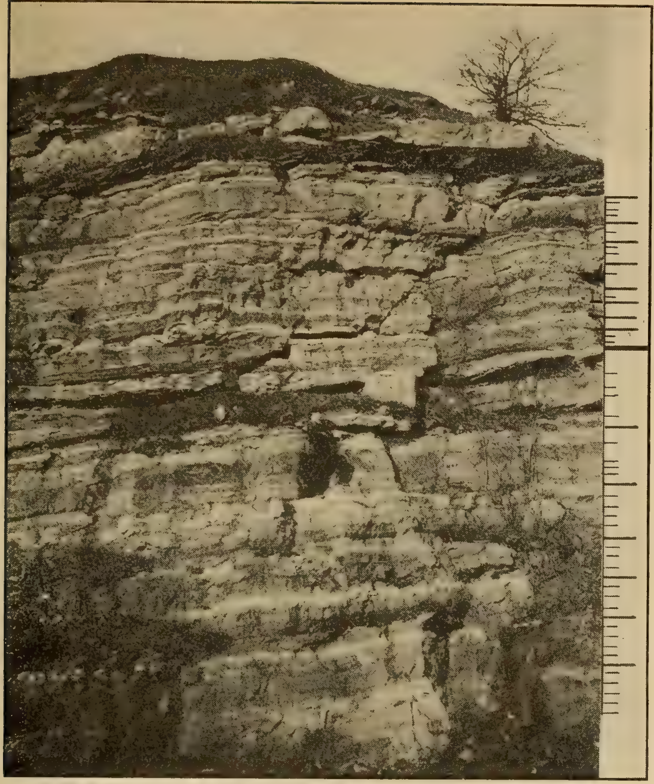

FIGURE 1.—CRYPTOZOAN LIMESTONE, WEST BANK LEHIGH RIVER, NORTH OF ALLENTOWN, PENNSYLVANIA

Photograph by W. A. Bell, 1914

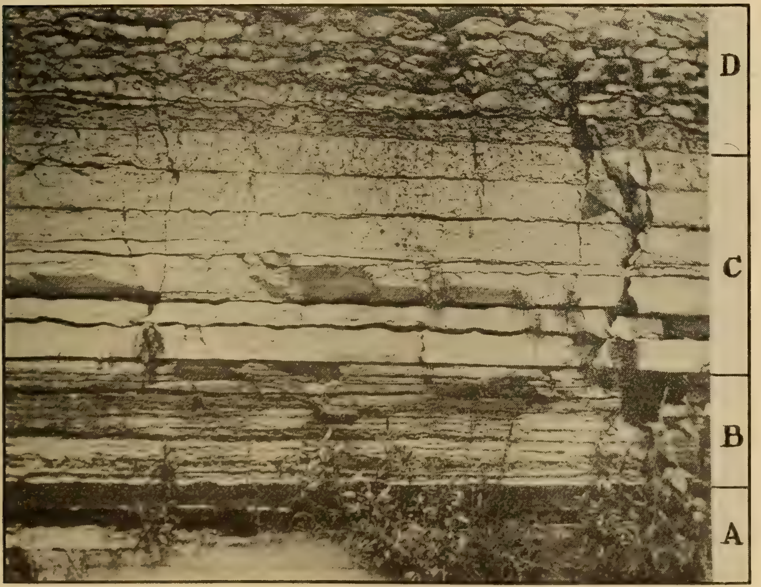

FIGURE 2.—CONTACT OF LOWVILLE AND BLACK RIVER LIMESTONES, NEWPORT, NEW YORK

Photograph by P. E. Raymond

LIMESTONE EXPOSURES IN PENNSYLVANIA AND NEW YORK

and are interbanded with fine-grained dark gray limestone. Detailed examination brings to light the fact that the cryptozoa were periodically blanketed by a soft lime mud, following which new colonies would start to grow on the layers of mud. The colonies were favored by clear water and became cemented crusts. These crusts, while yet thin, were liable to become broken up by wave action and form intraformational conglomerates. The thicker and stronger colonies had their existence terminated, not by wave action, but by becoming smothered beneath the next heavy invasion of mud. In some localities, however, the life of the colonies was probably terminated by draining away of water and drying, as shown by mud-cracking. Stronger wave action and influx of mud were thus the features determining the dark gray limestones; gentler wave action and clear water permitted the growth of cryptozoa. These conditions alternated in a markedly rhythmic fashion. The nature of the composite rhythm is shown well in the lower portion of the section. Many fine laminations, hardly visible in the photograph, make up a minor rhythm. Four or five repetitions of the minor rhythm led up to a crescendo favoring progressively longer times for the growth of cryptozoa. Then a sudden change took place to that phase favoring the accumulation of lime mud. In the upper third of the section the rhythm is seen to change in character; a lesser thickness is deposited in each cycle, the cryptozoan layers are sharper and thinner, the crescendo seems to have disappeared.

To what degree does this series of beds represent continuous or discontinuous deposition? Each cryptozoan colony doubtless lived a continuous life until it was smothered. The mud appears to have come in suddenly, since all parts of the colony stopped growing at once, both the base and top of the hemispherical turbans. There may thus have been a continuous deposition of alternately organic and inorganic nature, but at a variable rate. On the other hand, alternate fill and scour may have taken place during the deposition of the mud-beds. The rather abrupt change in the character of the rhythm may signify a loss of record during a time when the cryptozoan growth was stopped and before the colony was buried. Such a period of lost record would account for the sudden change in character, but on the whole the evidence suggests for this section the other explanation of sudden death by burial. The regularity and composite nature of the rhythm favors interpretation as a record of climatic oscillations and the whole section may represent a phase of a larger rhythm marked by a slowly subsiding bottom. T. W. Vaughan has shown that such a condition of submergence favors the growth of coral colonies, and the same was probably true of the cryptozoa. The following illustrations have been called to the writer's attention by Professor Schuchert, although three of the photographs are by P. E. Raymond, R. S. Bassler, and M. Y. Williams, respectively, who have kindly given permission for their publication.

The first, plate 44, figure 2, from the Middle Ordovician, shows the upper regular beds of the Lowville and the nodular lower beds of the Black River limestone. The Lowville, in the older nomenclature, was known as the bird's-eye limestone, from the preservation in it of the casts of vertical stems of marine plants, which seen in cross-section give the bird's-eye effect. The individual laminæ were therefore deposited rapidly and in shallow water. The formation consists of blue or dove-colored fine-grained limestones with beds of thin shaly limestone and shows an extraordinary persistence of lithologic characters over an area of 500,000 square miles, mainly east of the Mississippi River. A marked disconformity is pointed out by Ulrich as existing at the base of the Lowville, as it rests in places on the very similar, but far lower, Stones River limestone of the Lower Ordovician. Some of these limestones, probably including the Lowville, exhibit mud-cracks in many beds and in widely separated localities. The writer has also, but more rarely, found rain-printed surfaces. The Lowville is, however, very fossiliferous in certain layers; so that, although the waters were shallow and repeatedly withdrawn, they were typical marine waters. The oscillations must have been very small in amount and were perhaps mostly due to climatic factors, the seas forming marine playas. The overlying, or Black River, limestones are nodular and in places cherty, indicating a different character of deposition and probably much solution of lime in order to concentrate the silica. No large time elapsed, however, between the two formations, as Schuchert states in a personal communication that in the locality shown by the photograph he could not make out a faunal break at the top of the Lowville, but that there was clearly a depositional break, not a disconformity, however, in the generally accepted sense.

Referring to the photograph, the beds which are marked A, B, C constitute the upper Lowville; D, the Black River. There is exhibited here a striking series of rhythms. A major rhythm is represented by B, consisting of three subordinate beds. Each subordinate bed in B is subdivided in turn into three and these in their turn into thin laminæ. The weathering brings out a change by a series of steps from A to B to C, the latter consisting of six beds and being apparently equivalent to two rhythms of the value of A and B. The subordinate rhythms of B are almost absent from C. It is not thought that stress should be placed on the precise

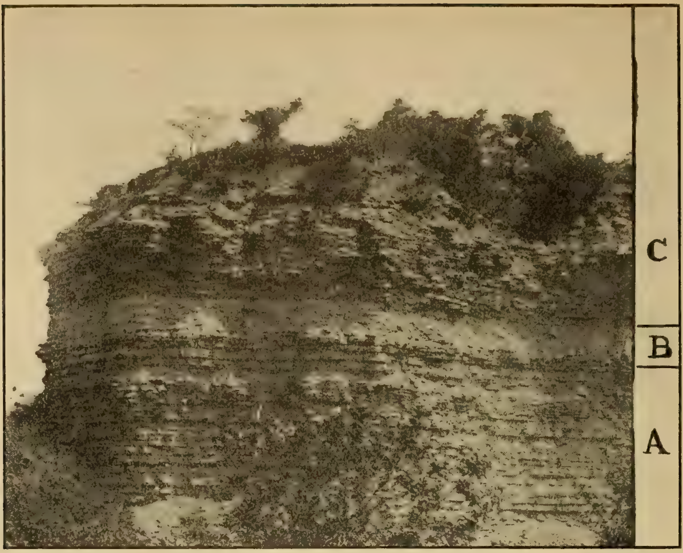

FIGURE 1.—BELLEVUE FORMATION RESTING ON THE FAIRMOUNT FORMATION. ERNST HILL, CINCINNATI, OHIO

Photograph by R. S. Bassler

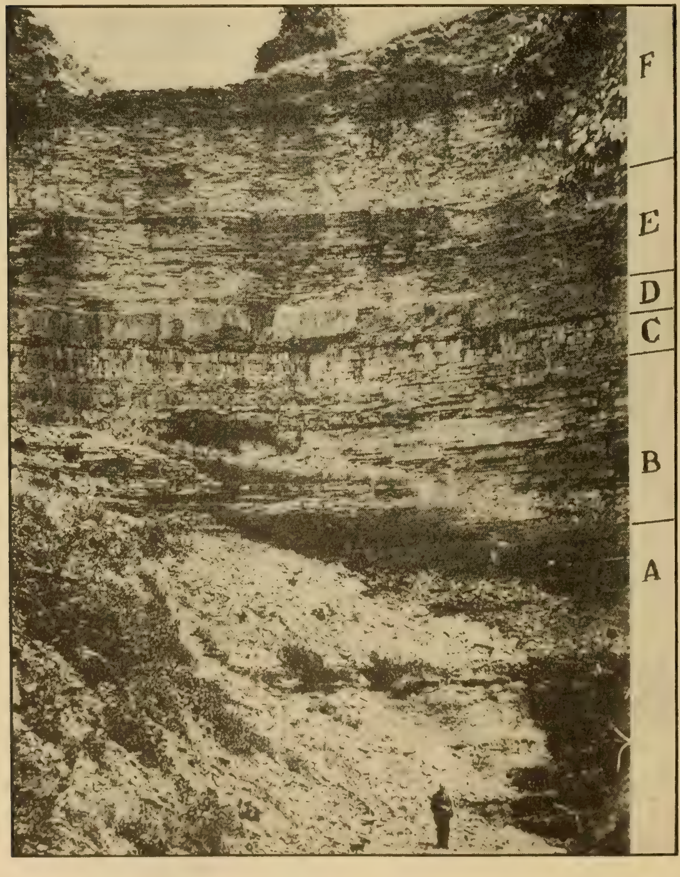

FIGURE 2.—SILURIAN SEQUENCE AT STONY CREEK, SOUTH OF HAMILTON, ONTARIO

Photograph by M. Y. Williams

EXPOSURES OF BELLEVUE AND FAIRMOUNT FORMATIONS, OHIO, AND SILURIAN SEQUENCE, ONTARIO nature of the rhythms, but it is regarded as very important that a rhythm runs with minor changes a certain distance through the strata and then comes to a full stop. It would be expected that, in a complete record, a rhythm should gradually emerge and disappear. The differences between A, B, and C are expressive, then, of well marked diastems between them. Lesser diastems divide the beds which make A, B, and C. Between C and D is a diastem of such large value that when sedimentation was resumed in D the nature of the rhythm had entirely changed. If this series is interpreted in accordance with the harmonic rhythms shown in figure 5, it is seen that a composite oscillation of baselevel with alternate fill and scour would account for the observed features of the beds. Each of the finest laminæ may have been deposited in a year, but the whole may represent only a fifth, tenth, or smaller fraction of the entire time. A long time interval is implied by the diastem between C and D, probably longer than the time represented by the whole of the Lowville formation, though not great enough to produce a notable faunal change on the resumption of the stratigraphic record.

The next illustration, plate 45, figure 1, showing also a change in rhythms, is from the Maysville or Lorraine group, which is the middle group of the Upper Ordovician or Cincinnatian. The Lorraine sea, according to Schuchert, was a somewhat limited flood covering most of the area between the Mississippi, the Appalachian land on the east, and the region of the Great Lakes. Winchell and Ulrich make the following statement regarding the section in Ohio:

> "At the base of the (Lorraine) division, which at Cincinnati comprises about 200 feet of strata, there are some arenaceous layers that on weathering frequently preserve the fossils as casts. Above these there are numerous layers of crystalline limestone, 3 to 10 inches in thickness, separated by relatively thin bands of shale. In the upper 60 or 70 feet the bedding is more irregular and the limestone layers thinner and generally argillaceous, unfitting them for building purposes. Fossils are well preserved and exceedingly plentiful and among them may be recognized nearly every species that has been described from the equivalent beds in New York." [33]

All the stratigraphic features indicate shallow water. The crystalline limestones suggest alternating undersaturation and supersaturation of the water, with alternate solution and precipitation of what was originally organic debris. The abundant fossils suggest periodic rapid burial in wave-stirred muds. A long period of time is represented by a very limited depth of strata. In fact, on a diastrophic basis, the Cincinnatian may come to be given the value of a geologic period. It is to be expected, therefore, that diastems occur here in rhythms of smaller and larger time values. In the photograph, A constitutes the Fairmount, B and C the Bellevue. Ulrich and Bassler consider that there is a well marked break between A and B. Bassler states in a personal communication that:

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[33] B. Willis: Index to the stratigraphy of North America. Prof. Paper No. 71, U. S. Geol. Survey, 1912, p. 166.

> "Between B and C strata come in, away from Cincinnati, sometimes to a thickness of 50 feet, which are represented around Cincinnati only occasionally by an inch or so. These are the Orthorhynchula beds which are so well developed in central Tennessee. This is only one of the unconformities which have been noted in the Cincinnati section where hitherto the rocks have been supposed to record continuous deposition."

In A there is a very marked rhythm which is not present in B or C. It would seem, therefore, that the disappearance of the rhythm indicates a long time interval and is in accordance with the evidence given by Bassler. The difference between B and C may indicate a lesser diastem. The significance of a sudden change of rhythm is the feature of this section which is most noteworthy.

The next illustration, plate 45, figure 2, is from the lower part of the Silurian. The sequence is given as follows by Williams:

F. Lockport dolomite, thin bedded.
E. Rochester shale.
D. Irondequoit limestone, thick bedded, top of Clinton.
C. Walcott limestone, thin bedded, Clinton.
B. Medina sandstone, thin bedded.
A. Cataract sandstone and shale, Schuchert, thin bedded.

Schuchert states that there is no clear faunal break here. This organic evidence of a disconformity is therefore absent, but the great lapse of time and the many sharp changes in sedimentation may be taken as evidence of the existence of diastems of large time value, approaching the nature of disconformities. The absence of faunal breaks would appear to be a proper basis for classifying the hiatuses as diastems.

In plate 46, figure 1, is shown a section which brings into one view formations of widely differing ages. The formations represented are given by Schuchert as follows:

E. Chattanooga black shale, Mississippian.
D. Onondaga limestone, 6 feet, Middle Devonian.
C. Louisville limestone, Middle Silurian.
B. Waldron shale, 9-10 feet, Middle Silurian.
A. Laurel limestone, Middle Silurian.

Willis summarizes the statements of Foerste, Kindle, and Barnett in regard to these Silurian formations of the Niagaran epoch as follows:

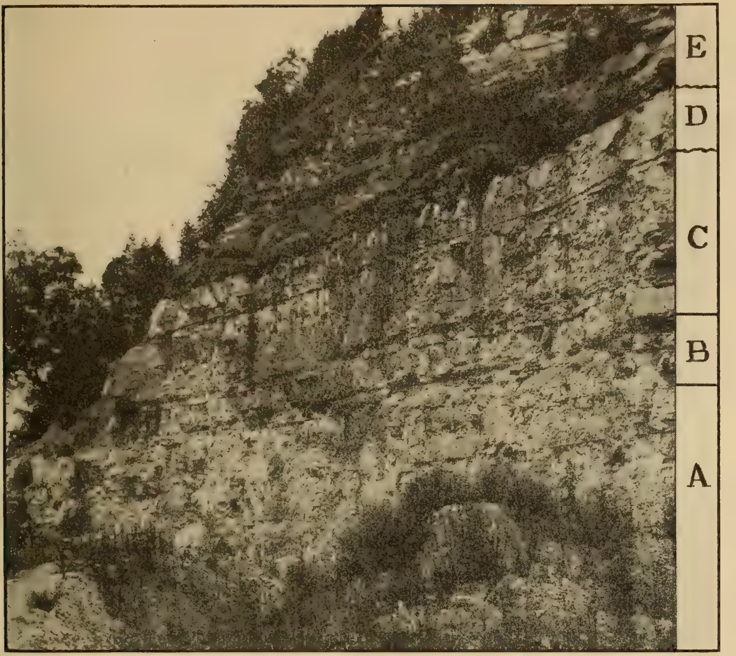

FIGURE 1.—SILURIAN, DEVONIAN, AND MISSISSIPPIAN SUCCESSION WEST OF NEWSOM, TENNESSEE

Photograph by C. Schuchert

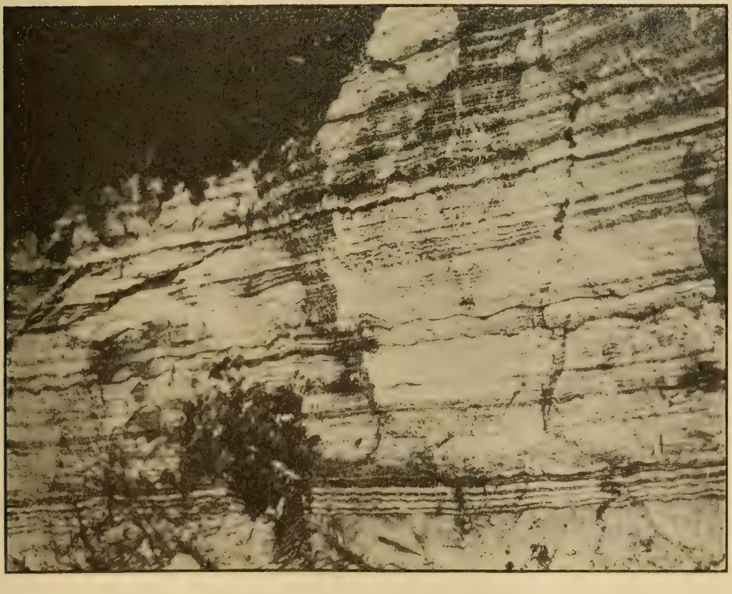

FIGURE 2.—GYPSUM, WINDSOR FORMATION, MISSISSIPPIAN, NEAR MONCTON, NEW BRUNSWICK, CANADA

Photograph by C. Schuchert

EXPOSURES OF SILURIAN, DEVONIAN, AND MISSISSIPPIAN IN TENNESSEE AND CANADA

"The Laurel limestone is usually hard, white, and evenly bedded. Toward the south it becomes softer and more argillaceous.

"The Waldron shale is a distinct bed overlying the Laurel, and is mainly a clayey shale having the facies of the Osgood shale. It becomes calcareous toward the north.

"The Louisville limestone, which at Louisville is unconformably overlain by Devonian limestone and has a thickness of 55 feet, is described as thinning out toward the north and east.

"The faunas of the several divisions of the Silurian in Indiana are distinguished by Foerste, who recognizes close affinities between those of the Laurel and Louisville on the one hand and between those of the Waldron clay and Osgood clay and limestone (below the Laurel limestone) on the other."[34]

This section is seen to illustrate a series of disconformities of lesser and greater time value. Without the testimony of the fossils there would be no evidence of the great lapses of time unrepresented by sediments. It is eloquent of the imperfection of the stratigraphic record and of the lack of necessary relation between the thickness of a section and the time represented, in that apparently conformable strata of three periods are shown in one quarry face.

Plate 46, figure 2, is a view of gypsum beds showing the rhythmic crinkled banding in a chemical precipitate. Here the changing concentration of the water may be due to changes in climate or to changes in the freedom of access of sea-water to the lagoons in which precipitation proceeded. The well marked composite rhythm is best seen by looking at the photograph from a distance or with nearly closed eyes, and the regularity of this rhythm suggests that it is a climatic record rather than one owing to the shifts in physical geography. Each lamina represents a stage of warmth and concentrating water; each surface of separation represents a shorter or longer period of undersaturation and consequent absence of record. Gradations may represent continuous deposition, but with changing rates. Such a series of beds is worthy of very careful analytical study as a detailed meteorological record of the past.

PART III.—ESTIMATES OF TIME BASED ON GEOLOGIC PROCESSES

MAGNITUDE OF THE CENOZOIC ERA ON EVIDENCE CHIEFLY FROM EROSION

Time is measured by the recurrence of rhythms or by the aggregate effects which are accumulated during their passage. The two preceding parts of this article have dealt with the importance of rhythms in modifying the rates of erosion and sedimentation; yet it is seen that previous attempts to sound the depths of geologic time have in nearly all cases assumed a uniformity of processes or have made but slight allowance for their variation. In this part a review will be given of the relations of methods to results and the assumptions on which those methods rest. The trend of the modifications indicated by the recognition of the importance of rhythms may then be perceived. It is not the intention to give a formal review of the many previous estimates which have been made of geologic time, since that has been done by others,[35] but merely to present that which seems essential in the present connection.

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[34] B. Willis: Index to the stratigraphy of North America. Prof. Paper No. 71, U. S. Geol. Survey, 1912, pp. 232, 233.

One of the earliest estimates was based on the evidence of life transformations in successive periods. Lyell divided the geological series into twelve periods and estimated—perhaps guessed would be a better word—that 20,000,000 years were demanded for a complete change in the species of each period, or 240,000,000 years in all. This estimate excluded the Primordial of Barrande and the "antecedent Laurentian formations." [36] Darwin considered that Croll's estimate of 60,000,000 years since the Cambrian period and the previous 140,000,000 years can hardly be sufficient for organic evolution.

From the physical side, the early geologists saw no indications of infancy or of old age on the face of Nature. Nothing less than interminable time broken into periods by revolutions appeared to be the testimony of the rocks. Lord Kelvin first called attention to the fundamentally erroneous nature of this conception. Of Kelvin's work A. Geikie states:

> "He pointed out that from the high internal temperature of our globe, increasing inwards as it does, and from the rate of loss of its heat, a limit may be fixed to the planet's antiquity. He showed that so far from there being no sign of a beginning, and no prospect of an end, to the present economy, every lineament of the solar system bears witness to a gradual dissipation of energy from some definite starting point.
>
> "But physical inquiry continued to be pushed forward with regard to the early history and antiquity of the earth. Further consideration of the influence of tidal friction in retarding the earth's rotation, and of the sun's rate of cooling, led to sweeping reductions of the time allowable for the evolution of the planet. The geologist found himself in the plight of Lear when his bodyguard of 100 knights was cut down. 'What need you five-and-twenty, ten or five?' demands the inexorable physicist, as he remorselessly strikes slice after

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[35] See especially C. D. Walcott: Geologic time as indicated by the sedimentary rocks of North America. Journal of Geology, vol. i, 1893, pp. 639-676; Smithsonian Report for 1893, pp. 301-334, 1894.

Arthur Holmes: The age of the earth. Harper and Bros. London and New York, 1913.

[36] Principles of Geology, 10th ed., 1867, vol. 1, p. 301. Quoted from C. D. Walcott, Smithsonian Report for 1893, p. 303, 1894.

slice from his allowance of geological time. Lord Kelvin is willing, I believe, to grant us some twenty millions of years, but Professor Tait would have us content with less than ten millions." [37]

Huxley in 1869 had refused to be limited by Kelvin's reasoning, considering that unknown factors may vitiate the results.[38] Geikie in 1892 states of it also:

> "That there must be some flaw in the physical argument I can, for my own part, hardly doubt, though I do not pretend to be able to say where it is to be found. Some assumption, it seems to me, has been made, or some consideration has been left out of sight, which will eventually be seen to vitiate the conclusions, and which when duly taken into account will allow time enough for any reasonable interpretation of the geological record." [39]

In 1903 Geikie states:

> "Until it can be shown that geologists and paleontologists have misinterpreted the records contained in the earth's crust, they may not unreasonably claim as much time for the history revealed in these records as the vast body of accumulated evidence appears to them to demand. There is a general agreement among the geologists that, so far as the phenomena of sedimentation and tectonic structure are concerned, 100 millions of years would probably suffice for the completion of the geological record. But if on paleontological grounds the allowance of time should be found too small, there appears to be no reason, on at least the geological side, why it should not be enlarged, as far as may be found needful for the satisfactory interpretation of the evolution of organized existence on the globe." [40]

Nevertheless, it is evidently true that, from among the various possible interpretations of the data, geologists were in general inclined to choose those which gave the lower limits to geological time. Such estimates which limited the earth to a duration of 100,000,000 years or less were easy to attain by taking fairly rapid rates of erosion and sedimentation and assuming that these represented the average of geological time. To show how wide are the limits as given by estimates based on geologic processes, the various modes of attack must be enumerated.

First to be taken up are those concerning the duration of the latest periods as determined especially by the erosion history rather than by the record of sedimentation.

Upham, who holds to the view that the Pleistocene consisted of one advance and retreat, concluded that the

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[37] A. Geikie: Geological change and time. Presidential address, Brit. Asso. Adv. Sci., 1892. Ann. Rept. Smithsonian Institution for 1892, pp. 124, 125.

[38] T. H. Huxley: Presidential address, Geol. Soc. London. Quart. Jour. Geol. Soc., vol. xxv, 1869, pp. xxxviii-liii.

[39] A. Geikie: Loc. cit., p. 126.

[40] A. Geikie: Text-book of Geology, 1903, pp. 77-78.

"probable length of Glacial and post-Glacial time together is 30,000 or 40,000 years, more or less; but an equal or considerably longer preceding time, while the areas that became covered by ice were being uplifted to high altitudes, may perhaps with good reason be also included in the Quaternary era, which then would comprise some 100,000 years." [41]

On the other hand, Chamberlin and others, recognizing the complexity of the ice-advances and basing their estimates upon the degree of erosion of the older glacial deposits, obtain a period of 300,000 to 1,020,000 years from the present to the Kansan glacial stage, and an unknown greater time to the beginning of the Pleistocene.[42] McGee, comparing the relative erosion of river valleys in post-Glacial and post-Columbian (early or middle Pleistocene) time and the work of erosion in the Tertiary, obtains a mean estimate of 200,000 years as the duration of post-Columbian time and 90,000,000 years for the Cenozoic.[43]

Goodchild takes the time since the close of the Glacial period as 20,000 years. He then makes an estimate of the time needed for the erosion of the Skye volcano. This he takes as beginning to erupt some time in the Oligocene, completed by the close of the Miocene, and as having an initial height of 8,000 feet. Choosing an erosion rate for its gabbroic rocks as one foot in 2,000 years gives an estimate of 16,000,000 years since the close of the Miocene.[44]

Dana obtained ratios of the relative durations of the geologic periods by comparing the volumes of sediment deposited in them. Taking the Quaternary as 1,000,000 years, the length of the Tertiary is 3,000,000. Ward, in the Fifth Annual Report of the United States Geological Survey, gives a time ratio to the Quaternary-Recent as 1, the Miocene-Pliocene as 1, and the Eocene as 1, and Williams adopts these ratios.[45]

These estimates by American geologists are no doubt the basis for a very common statement of the length of the Tertiary as 3,000,000 years. They were probably based originally on a comparison of the rather thin Tertiary deposits of the Atlantic coastal plain, the presence of many unconformities being then unappreciated. At that time the magnitude of Tertiary erosion and sedimentation in the regions of mountain-making was also uncomprehended. Year by year it becomes clearer that, since the opening of the Miocene, uplifts resulting in a greater or less completion of erosion cycles have been repeated several times. Blackwelder has discussed these features for the mountains of central Wyoming.[46] The magnitude of the work of erosion and the number of events since the opening of the Miocene are also illustrated in the Coast ranges of California. The newer interpretations of the structure and erosion history of the Alps testify to the great length and complexity of the geological history of the Miocene and Pliocene as compared to the Pleistocene.

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[41] Upham: Am. Jour. Sci., vol. xlv, 1893, pp. 217, 218.

[42] Chamberlin and Salisbury: Geology, vol. iii, 1906, p. 420.

[43] W J McGee: Note on the age of the earth. Science, vol. xxi, 1893, p. 309.

[44] J. G. Goodchild: Vice-presidential address. Royal Physical Society of Edinburgh, Nov., 1896, pp. 263-265, 1897.

[45] H. S. Williams: The elements of the geological time scale. Jour. Geol., vol. i, 1893, p. 295.

The maximum thicknesses of sediments deposited in the several periods have been made the basis by Sollas of estimates of age. The increase in knowledge concerning the divisions of the Tertiary is represented by the increase in his figures from the year 1900 to 1909. These are as follows:[47]

	A. D. 1900	A. D. 1909
	Feet	Feet
Recent and Pleistocene	4,000	4,000
Pliocene	5,000	13,000
Miocene	9,000	14,000
Oligocene	12,000	12,000
Eocene	12,000	20,000
	42,000	63,000

Turning to a reinterpretation of the data, it is to be noted that disconformities and unconformities occur between many of the formations, and reasons have been discussed in connection with the significance of valley forms for believing that the mean rate of denudation through the Tertiary probably has not equaled more than half of the rate for the Pleistocene and the Recent. From these varied lines of evidence it seems reasonable to regard the total Pleistocene as at least 1,500,000 years in length, and the younger Tertiary, including the Miocene and Pliocene, as perhaps ten times as long as the Pleistocene. But back of the younger Tertiary lies the earlier Tertiary. This was formerly all embraced in the Eocene and lower Miocene, but is now subdivided into Oligocene and Eocene, and the basal Eocene in turn is now set apart by many as the Paleocene. The older Tertiary was probably considerably longer than the younger Tertiary, perhaps twice as long, and the whole of the Cenozoic is as much as twenty and more probably thirty times the length of the Pleistocene.

Another line of attack is found in estimates of the amount of organic evolution accomplished in successive epochs, not forgetting, however, that, as evolution depends largely upon changes in environment, the times of rapid change will also be times of rapid evolution. No one is better qualified than W. D. Matthew to weigh this evidence for the evolution of the mammals through the Cenozoic. He has discussed this especially for the horses, but finds the results supported by a comparison with the evolution in other mammalian phyla.[48] On this basis Matthew estimates that the entire Tertiary is about one hundred times as long as the Pleistocene, dating the latter from the first great glacial advance. His impression from the evolution of vertebrates during the Mesozoic is that each of its four periods were comparable in length to the Tertiary. Matthew then raises the question as to what length of time should be adopted for the Pleistocene, the unit of measurement. He takes 100,000 years as representative of the more moderate figures between the 25,500 years of Wright and the 1,500,000 of Penck and other authorities. The resulting estimate of 10,000,000 years for the Tertiary and 40,000,000 for the Mesozoic does not seem to Matthew unreasonable.

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[46] Eliot Blackwelder: Post-Cretaceous history of the mountains of central western Wyoming. Jour. Geol., vol. xxiii, 1915, pp. 97-117, 193-217, 307-340.

[47] W. J. Sollas: Presidential address. Quart. Jour. Geol. Soc., vol. 65, 1909, p. cxii.

Matthew's results show a leaning toward higher estimates than nearly all stratigraphic geologists have admitted, but he has kept them down only by adopting what will seem to most students of the Pleistocene an ultra-conservative estimate of its shortness. With the recognition of the complexity of the Pleistocene and the amount of diastrophism and erosion accomplished in it, 500,000 years has come to be set as a minimum estimate of its length, rather than 100,000 years. As an upper limit, on the other hand, 1,000,000 to 1,500,000 years are not unreasonable figures, and the higher of these is adopted by Penck, one of the foremost authorities on the Pleistocene. Using only 500,000 years as the unit, Matthew's ratios give a length of 50,000,000 years for the Cenozoic and 200,000,000 years for the Mesozoic. These figures for the length of the Cenozoic and Mesozoic the writer believes to be of the right order of magnitude and supported by strong evidence, to be brought out in the later part of this paper.

The foregoing discussion suggests that the early estimate of 3,000,000 years, which has entered so largely into geologic literature, may well be multiplied by twenty. The evidence from radioactivity, to be presented later, suggests that 60,000,000 years may readily be granted to the Cenozoic era, and the geologic evidence as interpreted in this article is in harmony with this magnification, though, being qualitative rather than quantitative, it could, if necessary, be interpreted in terms of half this time. The geologic evidence can not be adjusted, however, to an age as short as 10,000,000 years without ignoring the factors discussed in the earlier parts of this article, and the estimate of 3,000,000 years is clearly an inheritance from a time before a proper geological perspective had been attained.

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[48] W. D. Matthew: Time ratios in the evolution of the mammalian phyla. A contribution to the problem of the age of the earth. Science, vol. xl, 1914, pp. 232-235.

MAGNITUDE OF THE PALEOZOIC ERA ON EVIDENCE CHIEFLY FROM SEDIMENTATION

Estimates of the duration of the Paleozoic era rest especially upon the rate of accumulation of the strata and the valuation of the intercalated disconformities and unconformities. In order to perceive if the data can be equally well or even better interpreted to give greatly longer estimates of time than has been customary, the lines of reasoning of two leading geologists will be examined, Walcott and Sollas, since their work has had great influence on geologic thought in these matters.

Walcott, in his vice-presidential address before Section E of the American Association,[49] gave the results of a careful study of the deposits of the Cordilleran sea as a basis for estimating the length of Paleozoic time. Giving ratios to the Paleozoic, Mesozoic, and Cenozoic as 12, 5, and 2, he obtained the following results:

Period	Time duration Years
Cenozoic, including Pleistocene	2,900,000
Mesozoic	7,240,000
Paleozoic	17,500,000
Algonkian	17,500,000
Archean	10,000,000 (?)

Walcott then states:

> "It is easy to vary these results by assuming different values for area and rate of denudation, the rate of deposition of carbonate of lime, etcetera; but there remains, after each attempt I have made that was based on any reliable facts of thickness, extent, and character of strata, a result that does not pass below 25,000,000 to 30,000,000 years as a minimum and 60,000,000 to 70,000,000 years as a maximum for post-Archean geologic time. I have not referred to the rate of development of life, as that is virtually controlled by conditions of environment.
>
> "In conclusion, geologic time is of great but not of indefinite duration. I believe that it can be measured by tens of millions, but not by single millions or hundreds of millions of years." [50]

As a basis for these figures Walcott takes the area of the Cordilleran sea as 400,000 square miles, the area of Cambrian drainage into it as 1,600,000 square miles, a minimum thickness of Cambrian mechanical sediments below the Upper Cambrian as 10,000 feet, a rate of erosion of one foot in 200 years and a deposition rate of one foot in 50 years. This rate he regards as more probable than slower ones, "in view of the evidence of rapid accumulation contained in the strata themselves." These basal assumptions give 500,000 years for the 10,000 feet of strata.[51]

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[49] C. D. Walcott: Geologic time, as indicated by the sedimentary rocks of North America. Smithsonian Report for 1893, pp. 301-334, 1894; Jour. Geology, vol. iii, 1893 pp. 639-676.

[50] Jour. Geology, vol. i, pp. 675, 676.

"In dealing with the post-Middle Cambrian mechanical sediments we have a somewhat different problem, but, as a whole, rapid deposition is indicated. For instance, the Eureka quartzite of the Upper Ordovician is a bed of sandstone, varying from 200 to 400 feet in thickness, distributed over a wide area—perhaps 50,000 square miles. It is made almost entirely of a white, clean sand that was deposited in so short an interval that the Trenton fauna in the limestone beneath it and in the limestones above it is essentially the same. The sand appears to have been swept rapidly into the sea and distributed by strong currents. The same is true of the 3,000 feet of the Lower Carboniferous sand and the 2,000 feet in the upper portion of the Carboniferous, while the shales of the Upper Devonian accumulated more slowly. In this connection we must bear in mind that during the long periods in which the calcareous sediments forming the limestones were being deposited the tributary land areas were in all probability baselevels of erosion, and chemical denudation was preparing a great supply of mechanical material that, on the raising of the land, was rapidly swept into the sea and distributed. In this manner the time period of actual mechanical denudation was materially shortened, yet, on account of the manifestly slower deposition of the Devonian shales, the rate of denudation should be assumed as less than during Cambrian time.

"In post-Cambrian time the area of the land surface was materially reduced by subsidence, which did not, however, greatly extend the Cordilleran sea, and it may fairly be estimated at 600,000 square miles. The depth of mechanical sediments already estimated is 5,000 feet and their volume at two billion mile-feet. Dividing the volume by the area of erosion, we get 3,300 feet as the depth of erosion required.

"Again, applying different rates of erosion, with allowance for slow progress of degradation during Devonian time, we have:

"*Post-Cambrian mechanical Sediments*

Rate of erosion over land area of 600,000 square miles.	Time required for removal of 3,300 feet.	Rate of deposition in sea of 400,000 square miles for 5,000 feet of strata.
1 foot in 3,000 years........	9,900,000 years.......	1 foot in 1,980 years, or .006 inch per annum.
1 foot in 1,000 years........	3,300,000 years.......	1 foot in 660 years, or .09 inch per annum.
1 foot in 200 years..........	660,000 years.......	1 foot in 132 years, or .18 inch per annum.

"The rate of one foot in 200 years is assumed as the most probable and 660,000 years as the time required for the removal and deposition of the 5,000 feet of post-Cambrian mechanical sediments."[52]

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[51] Loc. cit., p. 663.

[52] Loc. cit., pp. 664, 665.

In discussion of Walcott's statements it may be said that, according to his view previously cited, the rate of development of life is controlled by conditions of environment and can not by itself be used very securely as evidence for the shortness or length of time needed for the accumulation of a formation.

The argument has been stated in Part I that a peneplain is not a favorable land surface for the promotion of deep chemical denudation, and can hardly be invoked with safety in aid of a postulated rapid accumulation of sediment. The cleanness of a sand formation, on the other hand, speaks of prolonged sorting and is favored by fill and scour, pronounced wave or current action, and, notwithstanding the rapid accumulation of individual beds, may be accompanied by a slow aggregate rate of accumulation. Thus the principles of rhythms are of peculiar force in such a deposit.

With the conditions of low relief of the land a rate of erosion of one foot in 3,000 years seems more probable than one foot in 200 years. Even this is twice the present rate of erosion for the Mississippi basin, and about three times the rate given by Clarke for the present mean of the continents. It is probable, however, that the retarding effect of land vegetation was not then effective, so that a fairly rapid rate of one foot in 3,000 years for the low lands of the early Paleozoic may be provisionally accepted. But even this low rate gives a length of time fifteen times that regarded by Walcott as the more probable.

On the other side of the question, it may be said that if the mechanical sediments were derived from the unconsolidated deposits of an uplifted coastal plain, the rate of denudation of rock becomes immaterial in the making of the final formation. The unconsolidated deposits may be washed off almost as fast as uplift of the plain occurs, and deposited as fast as subsidence of the sea-floor permits. The time required to develop the original clastic material depended, however, on the rate of rock denudation. The time represented by the final and permanent accumulation of 10,000 feet of clastic sediments may consequently be short or long, according to the rate of crust movements, but with the probabilities in favor of millions, or tens of millions, rather than hundreds of thousands of years.

As a basis for estimating the time needed for the deposition of the Paleozoic limestones of the Cordilleran sea, Walcott takes the quantity as amounting to an average thickness of 2,250 feet over an area of 400,000 square miles. The calcium carbonate can not be regarded as derived only from the tributary land drainage, since the epeiric sea was in communication with the open ocean. The estimate must rest, then, upon many uncertain factors. Walcott, as the result of his discussion, estimates the area of Paleozoic lands supplying calcium to all the seas as 50,000,000 square miles, approximately the present land area of the globe. The area of ocean now accumulating calcareous oozes he takes as 52,500,000 square miles. The area of the Paleozoic epeiric seas in which lime accumulated he takes as 13,000,000 square miles, giving a total of 66,000,000 square miles as the total area of deposition at that time.[53]

"The area over which calcareous depositions was going on during Paleozoic time we have estimated at 66,000,000 square miles, which included the areas of the seas over the continental platform and those of the surrounding oceans. As the conditions appear to have been more favorable for the deposition of lime in the Cordilleran and Appalachian seas, we will assume that it was four times that of the open ocean.[54] With a land area of 50,000,000 square miles (*ante*, page 670) and a rate of chemical denudation of 70 tons per square mile per annum, the total calcium contributed to the ocean per year during Paleozoic time would be 3,500 million tons, or 3.78 times as much as that estimated for per annum at the present time, which is 925,866,500 tons (*ante*, page 668). This would have provided 50.7 tons for deposition per annum per square mile in the 65,000,000 square miles of ocean and seas and 202.8 tons for deposition per annum per square mile in the 400,000 square miles of the Cordilleran and 600,000 square miles of similar seas. On this basis 81,120,000 tons (36.4 mile-feet) were contributed per annum from the ocean water to the deposit in the Cordilleran sea; adding to this the 42,000,000 tons (18.8 mile-feet) contributed per annum by the denudation of the surrounding area to the Cordilleran sea, we have 128,120,000 tons (55.2 mile-feet) as the amount available for deposit per annum in the Cordilleran sea. At this rate it would have required 16,300,000 years to have deposited the 2,007,244,800 million tons (900 million mile-feet) of *calcium* in the Cordilleran sea; adding to this the 1,200,000 years estimated for the deposition of the mechanical sediments, we have a total of 17,500,000 years as the duration of Paleozoic time.

"In the estimate for the amount of chemical denudation the largest average is taken—70 tons of calcium per square mile per annum—and the assumption made that all calcium derived from the adjoining drainage was deposited within the Cordilleran sea. Again, the total supply provided per annum to ocean waters of Paleozoic time is taken as 3.78 times greater than the amount annually contributed to ocean waters today; of this, four times as much is assumed to have been taken out per annum per square mile as was taken by the remaining area in which calcium was being deposited.

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[53] Loc. cit., pp. 670, 671.

[54] Under the reduction of 50 per cent for the interbedded and intermingled mechanical sediments and 25 per cent for other material than calcium deposited from solution, the apparent amount of calcium deposited in the Cordilleran sea was greatly reduced. If this same ratio of reduction is applied to other Paleozoic limestone areas, I doubt if over 1,000,000 square miles will be found to contain as large an average amount of calcium per square mile as the Cordilleran area. On this account 1,000,000 square miles is the area taken for the greater rate of deposition of calcium during Paleozoic time.—C. D. W.

> "The area of the Cordilleran sea is given as 400,000 square miles, but it was probably 600,000, if not much more. It may be claimed that the area tributary to the Cordilleran sea was greater than I have estimated. The evidence, such as it is, is against such a view. As a whole, I think the estimate of 17,500,000 years for the duration of Paleozoic time in the Cordilleran area is below the minimum rather than above it." [55]

In discussing Walcott's results it should be noted first that Reade's estimate of 70 tons of calcium salts as the denudation rate per square mile per year for the globe consists of 50 tons calcium carbonate and 20 tons calcium sulphate. Clarke, on the basis of much better data, concludes that these figures are almost twice too large.[56] Instead of choosing a larger rate of supply to the ocean than the present, it would seem that it would be better to assume it as far lower. In Part I of this article reasons have been advanced for holding that the average relief of the Paleozoic was very low and the land areas suffering erosion were restricted. On this basis Walcott's results might be multiplied by five or ten.

As to the rate of deposition, Walcott makes no allowance for intervals of non-deposition. At the time he wrote it was generally believed that the Paleozoic seas reigned continuously throughout that era, but with somewhat progressively restricted areas. He was in advance of his time in showing that in the Lower Cambrian the continent was largely emerged, but there was not as yet any knowledge of the many disconformities which represent shorter and longer times of no record. The discontinuity of these Paleozoic water bodies is indicated on Schuchert's paleogeographic maps of successive epochs of the Paleozoic. A total of 36 maps is given for the Paleozoic. On five Schuchert shows no Cordilleran sea whatever. On 11 others it has but slight representation, the region of more permanent water being in Nevada and connecting with the Pacific or southern Atlantic waters.

It is clear that a higher rate of limestone deposition will take place in shallow, warm, and agitated waters; but that is only possible so long as the water is deep enough to prevent bottom-scour. Walcott chose a high rate of deposition of lime for a limited area over the globe, of which he reckoned the Cordilleran sea to be four-tenths, whereas it might perhaps equally well have been taken as not more than two-tenths of the area of the epeiric seas. The actual rate of deposition as controlled by the amount of subsidence was something less than this possible rate.

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[55] Loc. cit., pp. 672, 673.

[56] F. W. Clarke: A preliminary study of chemical denudation. Smithsonian Misc. Coll., vol. 56, no. 5, 1910, p. 5.

We may conclude consequently that because of times of non-deposition, because of partial limitation of deposition by lack of subsidence, and because of a less ratio of the Cordilleran sea to the total epeiric seas, the time involved may have been five or ten times longer than the time calculated by Walcott. Combining this with the reduction in the estimates of rates previously discussed, the total time is multiplied by the product of these corrections. The 16,300,000 years given by him as the estimate for the time needed for the deposition of limestones is clearly far too short. It might be multiplied by ten, twenty, or thirty to give the duration of the whole Paleozoic. A twenty- or thirty-fold multiplication would accord more closely with the estimates given by the uranium minerals, to be discussed later.

Attention should next be given to the estimates of geologic time made by Sollas, using the method advocated by Haughton—that the proper measure of the length of the successive periods is given by the maximum thickness of strata deposited in them. In 1895 Sollas estimated these thicknesses for the post-Archean to aggregate 164,000 feet, in 1900 he raised the sum to 265,000 feet, and in 1909[57] to 335,000 feet. The latter figure is distributed among the geological eras as follows: Cenozoic, 63,000; Mesozoic, 69,000; Upper Paleozoic, 63,000; Lower Paleozoic, 58,000; Proterozoic, 82,000; Archeozoic, no estimate.

These maximum thicknesses are deposited in geosynclines which may be taken as deepest in the middle and of a triangular cross-section. He takes a mean rate of denudation for all geological time of one foot in 2,400 years. To get the rate of deposition the drainage into the Gulf of Mexico is used, the drainage area being taken as 1,800,000 square miles and the area of deposition as 100,000 to 180,000 square miles. Sollas assumes consequently the mean deposition area for these thick formations as one-tenth of the erosion area. This gives a mean rate of deposition of one foot in 240 years. But in a triangular section the thickness of the middle is twice the mean thickness. This would give a rate in the region of maximum thickness of one foot in 120 years. But taking the sides of the triangle as somewhat convex upward, Sollas obtains a rate in the region of maximum subsidence of one foot in a hundred years. This gives for the sedimentation of the Paleozoic 12,100,000 years, and for all post-Archean time 33,500,000 years.[58]

In his earlier estimates Sollas made no allowance for the time represented by unconformities, but in his latest work, giving apparently greatest weight to the age of the earth as 80,000,000 years, based on the sodium content of the sea, he grants from 23,000,000 to 29,000,000 years for unconformities. By assuming Precambrian time to have been as long as later time, his total estimate from sedimentation is raised to the desired total of 80,000,000 years.[59] According to these estimates, the Paleozoic era was about 25,000,000 years in duration.

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[57] W. J. Sollas: Anniversary address of the president, Geol. Soc. London. Quart. Jour. Geol. Soc., vol. 65, 1909, pp. lxxxviii-cxxii.

[58] W. J. Sollas: The age of the earth and other geological studies, 1905, pp. 36-38.

In discussing Sollas' results, the first point to be noted is the rate of denudation chosen—one foot in 2,400 years. This is more than three times as rapid as the present mean for the whole earth determined by latest measurements, and more than twice as rapid as the rate of denudation for the Mississippi drainage basin, which, except for the Colorado, is given by Dole and Stabler as the highest of the twelve large drainage divisions of the United States. In defense of choosing such a high rate, it may be said that the maximum thicknesses in geosynclines have come especially from bordering uplands or mountains, but on the other hand these mountains were rapidly reduced in slope, long periods of quiet and low relief intervened between uplifts, and the average slope for the Paleozoic was certainly but a fraction of the present high reliefs. Instead of taking a mean rate of denudation as one foot in 2,400 years, the present mean rate might better have been taken, or the present rate might have been even divided by two, giving a denudation rate of one foot in 8,000 to 16,000 years—limits somewhat less than one-third to one-sixth of that which he used.

Sollas speaks of the coarseness of the geosynclinal deposits as proof of rapid deposition; but these coarse beds are only occasional, and the great bulk of the deposits are such as would have been carried by streams of gentle grade.

Turn next to his fundamental assumption of one to ten as the ratio of the deposition area to the denudation area. Instead of making careful estimates from many streams and comparing these to the geographic relations implied by the geosynclines, the Gulf of Mexico drainage is chosen offhand as a sufficient basis. It is doubtful if a poorer illustration could have been found; as is seen when it is noted that now, in a time of abnormal continental relief, the Mississippi and other streams gather together the waters and the waste from the broad interior and high mountainous tracts of a continent and converge it radially into a Mediterranean sea, the Gulf of Mexico, where the deposition is mostly on the slopes of a continental terrace.

The thick formations of the past are not deposits of the continental terrace, but are revealed by the erosion of compressed and folded troughs, These lay on the sides of ancient mountain systems facing the continental interiors. These geosynclines were great downwarps which were parallel with and related to great upwarps, the geanticlines. The latter supplied the bulk of the sediments which filled up the troughs. The continental interiors, on the whole, added little or nothing to them, since especially in the Paleozoic they were often the seats of shallow seas which received sediment carried across the geosynclines from the uplands. If waste was sometimes washed back into the geosynclines its ultimate source was nevertheless in greater part the mountainous uplands on the other side. Following the views of Suess, the geosynclines are to be looked on as genetically related to the geanticlines; the mountain ranges depress the forelands or foredeeps and the waste from the mountains is washed into these parallel troughs.

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[59] Quart. Jour. Geol. Soc., vol. 65, 1909, pp. cxiii-cxv.

The best present illustrations are found in association with the great Eurasian mountain systems upraised in the Neocene. The valley of the Po with the northern half of the Adriatic show filling by waste from the Alps and Apennines. The plains of Mesopotamia and the Persian Gulf constitute the catchment basin for the associated mountains. The Indo-Gangetic alluvial plains and deltas lie in front of the Himalayas. On examining the maps of such regions it will be found that the area of deposition instead of being one-tenth of the area of drainage, as assumed by Sollas, is approximately equal to it. The sediments of the geosyncline represent a mountain system eroded and inverted.

In times of low relief, however, the proportion of waste brought in from a distance might increase. Assume, then, that the waste of the geosyncline was derived on the average from a land of twice its area. Take the mean rate of denudation as between one foot in 8,000 years and one foot in 16,000 years. Using the other conditions regarding the shape of the geosynclinal prism as postulated by Sollas, the rate of accumulation of the maximum thickness becomes one foot in 1,650 to 3,300 years. Introducing an appropriate ratio for the times of non-deposition, it is seen that Paleozoic time may be anywhere from fifteen to thirty times as long as the estimate given by Sollas.

This rate of accumulation may seem intolerably slow to those used to thinking of sediments as rapidly deposited, as seen by the testimony of their structures. In reconciliation it should be pointed out that the principles developed under composite rhythms in Part II go to show that individual beds may be deposited with great rapidity as determined by the fluctuation of atmospheric and hydrospheric forces, and yet the formation can accumulate no faster than sediment is supplied by the mean rate of denudation. It will ordinarily accumulate more slowly, as shown by the maintenance of a baselevel surface of deposition, with its implication of the control of sedimentation by the slowness of subsidence.

The mean rate of subsidence in a geosyncline has apparently been such that a fairly large fraction of the mechanical sediment has been caught in it. This is shown by the frequent passage of shales into limestones within or beyond the bounds of the geosynclines. On the other hand, at the times of greatest diastrophism and continental emergence an unknown quantity of waste has been carried to the margins of the continental terrace and lost to observation. We may regard, then, as safe, a conclusion that the Paleozoic era was several hundred million years in length.

Notwithstanding the inexact nature of the total of geologic time as determined by the study of erosion and sedimentation, this line of attack will be valuable for estimating the relative duration of the different periods, the times and the totals being checked by some other and more exact method.

A few geologists have perceived the untenable nature of the assumption that denudation and sedimentation have progressed in the past at the present rate. Some have not published their views specifically. Those who have indicated this opinion in published articles which have come to the writer's attention are E. C. Andrews,[60] A. Holmes,[61] and A. Harker.[62]

In conclusion should be mentioned Goodchild's estimate, based on a detailed discussion of the stratigraphic sequence. He obtained 704,000,000 years since the beginning of the Cambrian, 93,000,000 being given to the Tertiary, 236,000,000 to the Mesozoic, 375,000,000 to the Paleozoic.[63] He reached these large figures by taking the rate of deposition of sandstone as one foot in 1,500 years; shales, one foot in 3,000 years; limestones, one foot in 25,000 years. He also considered the significance of unconformities. Goodchild, however, did not take into consideration many possible factors, such as the rhythmic nature of sedimentation and its ultimate control by subsidence; so that his estimate doubtless appeared to differ from others by a mere preference for the longer periods of time and in apparent conflict with the clear evidence of the rapid accumulation of individual beds. There is, however, much of value in his detailed discussion, and his results, published before the first estimates based on radioactivity, are in notable accord with those reached in the present study.

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[60] E. C. Andrews: Erosion and its significance. Journal and Proc. of the Roy. Soc. of New South Wales, vol. xlv, p. 132; read Aug. 2, 1911.

[61] Arthur Holmes: The age of the earth. London and New York, Harper Bros., 1913.

[62] A. Harker: Geology in relation to the exact sciences, with an excursus on geological time. Nature, March 25, 1915.

[63] J. G. Goodchild: Vice-president's address, Nov., 1896. Proc. Royal Physical Society of Edinburgh, vol. xiii, part 3, 1897, pp. 259-308.

The lack of notice given to his paper seems to have been due to a lack of that conclusive demonstration which is needed to force attention to a view not in accord with the times.

ESTIMATES OF TIME BASED ON RHYTHMS IN SEDIMENTATION

Through all of earth history the existence of a solid crust requires that, no matter how effective as a heat retainer is the atmosphere, the maintenance of the atmospheric and hydrospheric envelope in gaseous and fluid form has been due to solar energy, and not in any appreciable degree to heat derived from the earth. The solar heat is now and always must have been delivered in largest quantity to the equatorial zone and in small amount to the polar regions, yet the circulation systems are so efficient that even in this age of polar ice the temperature of the polar night falls only a little way comparatively toward absolute zero. The circulation system which spreads out the heat is kept in motion by the loss of heat in higher latitudes and the latitudinal difference in temperature which results. During most of geologic time the efficiency of the circulation system was so high that relatively small differences of temperature sufficed to maintain it.

But the spread of solar energy by means of the circulation systems from low to high latitudes and from seas to inland regions must always have been rhythmic. This is a very general condition, where speed of flow is limited by the resistances which are set up. In the irregularities of motion the flow seeks that direction where the resistances are temporarily lessened; increasing in speed, the resistances are increased until they in turn overcome the inertia of the motion. As a result, a cyclic damping of the flow is produced in the one place or time with a corresponding acceleration in another. Thus the flow of energy proceeds in pulses. The cyclonic storms of the temperate zones and the blizzards of the polar ice-caps illustrate short-term rhythms of this nature. The shifting of storm tracks and runs of similar weather may represent oscillations in equilibrium of longer term due to such terrestrial conditions. Such pulses may be classified as terrestrial climatic rhythms.

But similar laws of oscillation control the liberation of energy from the sun. To maintain its surface temperature, convective movements must stir its mass, actuated by loss of energy, manifested by cooling and condensation at the surface, renewed by the transformation of other modes of energy into thermal form at depth.

To begin with short-term rhythms and passing to those of longer term, a rhythm has been detected in the change in the frequency of solar prominences in a period of about three years.

The sun-spot cycle with an average length of 11.4 years is well known. Newcomb and others have recognized a slight effect in the mean annual temperatures, and Huntington and Douglass have shown that it finds terrestrial record in certain regions by fluctuations in the growth rate of trees.[64] The variation in time of culmination of sun-spots is, however, considerable, from 7 to 16 years, and the climatic effects are slight, the geological effects perhaps negligible.

Brückner detected a cycle of 35 years in the variations of glaciers and in the level of the Caspian Sea—a rhythm which has since been found to have its origin in the sun and corresponds nearly to three of the sun-spot cycles.[65]

The work of Douglass has brought to light a 21-year cycle in rainfall and tree-growth in Arizona, and less definitely a larger cycle of about 150 years.[66]

H. W. Clough, from the evidence contained in the catalog of early observations of sun-spots and auroras, compiled by Fritz, holds there is evidence extending back to about 300 A. D. of a solar cycle of about 300 years in length.[67]

As to the existence of long-term changes of climate during historic time, investigators as yet are not agreed. There are those who hold, from the distribution of crops and the dates of harvest, and from the freezing of rivers and harbors, that no appreciable change has taken place. This appears to be nearly true for the past thousand years, in so far as a regular or progressive change of climate is concerned; but the evidence seems to be good that within that time there have been centuries which departed appreciably from the mean. On comparing the conditions previous to the dark ages with later times, however, more notable changes begin to appear. These have been investigated in recent years chiefly by Huntington, and, although there are those who do not accept the results, the evidence in many respects seems to the present writer compulsory in its nature.

Huntington concludes from several methods of attack, but chiefly from the degree of habitability of arid lands, that the climate of such critical regions has varied notably and repeatedly during the historic period. Such changes might pass undetected in the regions of equable rainfall and temperature, except by means of precise scientific observations, but in semi-arid to arid regions the oscillations change to a large degree the quantity of life which can exist and compel the rapid migration of faunas. Such changes find geologic record through their effects on the carrying power of streams and the depth of wave action. There have been important fluctuations measured in centuries, and still more important ones which cover several thousand years. They appear, however, to be rather sudden and irregular in their inception. According to Huntington, the climate through the primitive historic era, dating from 3,000 + B. C. to 1,200 B. C. was on the average markedly cold and wet, but still showing oscillations. During the period from 1,000 B. C. to 500 A. D. there was a decrease in these conditions, and from 600 A. D. to the present there has existed a period of general warmth and aridity.[68]

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[64] E. Huntington: The climatic factor. Carnegie Institution of Washington, 1914, Publication No. 192.

[65] W. J. S. Lockyer: The solar activity, 1833-1900. Proc. Royal Soc., vol. 68, 1901, pp. 285-300; Nature, vol. 64, 1901, pp. 196, 197.

[66] Huntington: Loc. cit., p. 117.

[67] Astrophysical Journal, vol. xxii, 1905, pp. 42-75.

The work of Huntington joins on to that of the glacial geologists. Periods measured in centuries and in some thousands of years should find notable expression in glacial oscillations and result in the building of retreatal moraines. These climatic oscillations during the historic period are geologically of importance, in that they show the existence of such rhythms which are not due to the precessional period of 21,000 years, but which, if found recorded in the strata, might have been mistaken for it.

F. B. Taylor has published a valuable study on the moraines of recession which marked the retreat of the last ice-sheet from the Ohio River to the Great Lakes.[69] According to Taylor:

> "1. Between Cincinnati and Mackinac the Wisconsin drift formation has fifteen terminal moraines which form a consecutive series marking the retreat of the last ice-sheet, and there are three more farther north probably belonging to the same set. The series seems to be complete and is believed to constitute the simplest and most perfect known.
>
> "2. Making due allowance for the influence of topography, it appears that the intervals between the members of the series are remarkably regular, suggesting periodic halts or oscillations of the retreating ice-front, which appear to be attributable only to a periodic change of climate."[70]

Taylor tries to fit the series to the precessional cycle, as the only known cause, but finds 21,000 years too long. He states that a period of between 5,000 and 10,000 years would seem to accord most closely with the phenomena.

In Europe the retreat of the last ice-sheet was marked by three greater halts. These, beginning with the maximum, are as follows:

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[68] E. Huntington: Palestine and its transformations, chap. xvi, 1911.

[69] Moraines of recession and their significance in glacial theory. Jour. Geol., vol. v, 1897, pp. 421-465.

[70] Loc. cit., p. 464.

Depression of snow-line	Alpine stages	Scandinavian moraines
1,200 meters	Würm	
900 "	Bühl	Baltic
600 "	Geschnitz	Ra
300 "	Daun	Christiania Valley

Time from the Bühl stage has been estimated at from 16,000 to 24,000 years, with the probabilities in favor of the longer period. Time from the outer Ra moraine has been more closely estimated at 17,000 to 18,000 years. Time since the last stage is as much as 7,000 years. Minor retreatal moraines lie between these stages. There seem to be here a combination of two cycles, perhaps both irregular, the cycle discussed by Taylor having a mean period of 2,000 or 3,000 years, the other with a mean period perhaps as large as 10,000 years. In the interior of the North American continent the shorter of these cycles has left a more prominent record; on the northwestern shores of Eurasia the longer is the more conspicuous. Such a difference in emphasis of cycles of different periods in different regions is paralleled by what is known of the expression of the shorter climatic rhythms acting in recent times. The climate of the interior of North America is controlled by continental conditions; that of northwestern Eurasia by oceanic, especially by the nature of the Gulf Stream.

Changes up to this order magnitude are more readily ascribed to cycles in solar radiation than to other causes. Volcanic dust in the terrestrial atmosphere acts as a screen, but it is probably too sporadic and temporary in occurrence to lead to such periodic changes in climate. Furthermore, certain highly volcanic epochs, such as the Eocene and Oligocene, have been marked by warm and equable climates over high latitudes. In addition, the rather regular and pronounced climatic oscillations in the Pleistocene are not known to have been related to rhythmic outbursts of volcanic energy.

Changes in atmospheric composition or in crust movement are too slow and massive to be invoked for such changes as have been discussed, but are the probable causes in determining the character of geologic periods, as is shown by the concurrence of glacial climates at the culmination of periods of continental movement and revolution. The sharp oscillations of decades, centuries, and thousands of years in length may be classified as solar climatic rhythms; the long, slow, and massive movements, rhythmic in their character, as diastrophic climatic changes.

There is another class of recurrent changes most important for the measurement of time. These may be called orbital rhythms, depending on the motions in the solar system. They are familiar as the rhythms of the tides, of day and night, of the year, of the precession of the equinoxes, and of eccentricity of the earth's orbit.

Of these, the tides act as geological agents on embayed shores and in straits, but are too rapid in occurrence to leave, except rarely, a record of individual ebb and flow.

The alternation of day and night serves as an important geological agent in producing a rapid and marked rhythmic recurrence of temperature changes.

The temperature rhythm of the seasons is now felt in all but a few parts of the earth, and outside of the tropics enters strikingly into the nature of geological processes. Even the year, however, is too brief a space of time to find stratigraphic record except in special cases, the most notable perhaps being in the annual rhythm of clay and silt laid down on the bottoms of lakes, especially those which face glaciers and receive during the melting season an abundant supply of waste. One of the most striking facts of geologic history is, however, the absence of freezing cold through most of geologic times in middle and high latitudes. Celestial mechanics points with certainty to a fixity of the poles and a constancy in their inclination to the orbit of the earth. There must always, therefore, have been seasons of darkness in the polar zones and of diminished solar heat in middle latitudes. But in spite of this the testimony of fossils points to the general absence of severe cold or frost. At times of glaciation, however, evidence is found of marked seasonal changes in such latitudes, as in the banded argillites of Permo-Carboniferous age found by Sayles near Boston, Massachusetts, and in the Pre-cambrian banded argillites found in Ontario and in Sweden. It seems that in periods of glacial climates there is an emergence of winter. Winter, furthermore, must always have been present in continental interiors of higher latitudes as a season of more or less cold, especially whenever the climate was semi-arid or arid. The fur of mammals and the feathers of birds probably find their development in a more prevailing existence of seasonal change over the continents of the Mesozoic era than has been suspected from the biologic record of marine waters and of coal swamps. In sediments of fairly rapid accumulation the record of the seasons may have been somewhat more widely kept than is suspected. In all semi-arid continental deposits the recurrence of waters has probably had a seasonal basis. Generally, however, it is clear that the annual rhythm does not enter into the stratigraphic record, both because it is too rapid and has been too generally submerged. Even in the deposits of semi-arid fluviatile basins the strata are the result of far longer and deeper rhythms.

The oscillations of day and night, of summer and winter, have been of fundamental importance, however, not in stratigraphic record, but in the manner in which they have stamped their existence in the life rhythms of organisms. In a little perceived, but even more fundamental way, the diurnal and annual rhythms have been essential to evolution. They have hardened the endurance of plants and animals to changes of temperature and to the dangers of night and winter. From this ever-recurring annealing process organisms have acquired the power of adaptation to the longer rhythms of climatic change, and thus have been able to emerge sifted and improved from the climatic stress of critical periods.

The higher rhythm of precession has a mean period of 21,000 years, from which it may vary by about 10 per cent. It brings in no climatic change except by virtue of the eccentricity of the earth's orbit. Croll has made it familiar by his attempt to apply it as a cause of glaciation, but the lack of accord with the history of the glacial period, as it is now understood, has caused it to be generally discarded. Nevertheless, at times of high eccentricity of orbit it remains true that at one phase of the rhythm the summers in one hemisphere will be somewhat shorter and hotter, the winters somewhat longer and colder. The reverse effects will be felt at the same time in the opposite hemisphere. Every 10,500 years the relations of the hemispheres will shift, and thus a change in the character of the climate will be felt 21,000 years in length. The only question is: Can it rise to visible expression above the various other solar and diastrophic rhythms which are seen to have entered into the climatic oscillations of the Pleistocene and presumably extend backward with various expressions through the earlier periods?

The only rhythms which, because of their certain existence and unchanging length, are adapted to the measurement of geologic time are the regular orbital rhythms. The terrestrial and solar climatic rhythms are apparently too numerous and too irregular in period to serve as safe measures of time. Furthermore, in one region and at one time one rhythm may dominate, as the 21-year cycle in Arizona, and in another place or time another rhythm, such as that of the 35-year cycle in glacial advance and retreat. The oscillations which occur in centuries, in thousands of years, and in tens or hundreds of thousands of years are best adapted to be stratigraphically recorded; but their discrimination, their persistence, their regularity, and their mean period are all open to serious question.

Even if the precessional rhythm can be distinguished it can not bridge unconformities and in most formations surely does not appear; but if from time to time we can detect in the strata under favored conditions the beating of the precessional clock, valuable clues may be obtained as to the length of time required for the deposition of certain formations. It should be looked for under conditions where seasonal changes might be expected to affect the vegetation, the regimen of rivers, or the intensity of wave action in shallow seas. Such conditions are suggested in middle or higher latitudes, where temperate faunas and floras exist or where the deposits indicate the existence of a semi-arid climate. The evenly bedded fine-grained deposits in lagoons or on the floors of shallow seas would be more favorable than the irregular bedding of river plains. The deposits of lake bottoms or of fore-set slopes, or of sea-floors temporarily below wave-base, are perhaps the most favorable situations. Transition regions between two facies are most favorable, as where sheets of lime and clay sediments are interfingered. In such places a slight shifting of climatic factors is recorded by a more or less wide shifting of the border line between the facies. The shallow limestone seas of the earlier periods should be examined, for they show a marked oscillation in bedding, changing conditions in salinity, and varying turbidity of shallow waters.

To reach a conclusion an exposure should be extensive. The proof would be to find a thin lamination marking an annual rhythm gathered into higher rhythms, and these into still higher but fainter groupings, so that a restoration of the annual layers would aggregate about 20,000 in one of the larger and fainter groupings. This may seem difficult to attain, and a more favorable, but less conclusive, recognition of the precessional cycle may be sought in beds which probably represent each several centuries or some thousands of years, grouped into regularly recurring but faint rhythms, which shall comprise some tens rather than units or hundreds of the lesser beds. There may have been times, however, when the flow of solar energy was so smooth that the precessional rhythm could emerge into control and find stratigraphic expression. It would be marked by great regularity, but other rhythms may, however, rise into recurrent dominance and exhibit for a time a marked regularity, so that caution in identifying rhythms must be ever present.

The possibility of measuring the time of accumulation of strata by means of climatic rhythms has been dealt with rather fully, since notwithstanding the lack of definite results thus far obtained, it seems to contain large possibilities and should lie in the background of the mental vision ready to be invoked.

Many stratigraphic sections show notably regular rhythms in the alternations of beds. A few of the more conspicuous and regular may be cited.

Two remarkable formations, the Sausalito and Ingleside cherts, occur in the Franciscan group of probable Jurassic age.[71] The former is about

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[71] See A. C. Lawson: San Francisco Folio, U. S. Geol. Survey, No. 193, 1914.

900 feet thick in the San Francisco region and the latter about 530 feet. They are preceded and succeeded by thick sandstone formations and are separated by the Marin sandstone, 1,000 feet in thickness. The two chert formations consist of sheets of chert alternating with partings of shale. Lawson describes these formations and their conditions of deposition as follows:

"The thickness of the sheets of chert in the typical sections generally ranges from about 1 to 3 or 4 inches, averaging perhaps 2 or 3 inches. Some beds are much thicker, but the sections of the chert nevertheless in general show thin and even bedding. The shaly partings between these sheets usually range from about one-eighth to one-half inch in thickness, but many of them are mere films. As the formations are in some places exposed in sections that are several hundred feet thick, they present the remarkable phenomenon of an alternation of thousands of layers of chert, with as many layers of shale. In the common red phase of the formations the regularity of this thin-sheeted stratification is amazing. In other phases, in which red iron oxide is not so abundant, the regularity is much less marked and the sheets assume lenticular forms.[72]

"On a smooth surface of almost any specimen of these cherts a lens will reveal minute round or oval dark, hyaline, or whitish dots. These dots, which are scattered through the rock, prove on microscopic examination to be the remains of Radiolaria, the characteristic fossils of these formations. The Radiolaria are minute animals that thrive in sea-water and secrete siliceous skeletons of very complex structure. These skeletons evidently accumulated in great numbers on the floor of the sea while the radiolarian cherts were being deposited and thus contributed to their formation. As a rule, they are sporadically embedded in the siliceous matrix above described, but in some places they are so closely crowded as to constitute the greater part of the chert. Where the Radiolaria are scantily distributed through the chert it is uncertain whether or not the matrix also is derived from these organisms, and the alternative hypothesis that it was formed by the purely chemical precipitation of silica, supplied possibly by submarine springs, is worthy of consideration. If the silica is wholly of organic origin it must have been dissolved and reprecipitated in its present form as an ooze on the sea-bottom.

"As subsidence proceeded the detrital material washed from the receding shore again failed to reach the region and organic agencies once more resumed sway. This time, however, calcareous organisms were replaced by those which secrete silica from the sea-water, so that the sea-bottom was covered with radiolarian ooze, which eventually consolidated as the Sausalito chert. The rhythmical oscillation of conditions which produced the remarkable alternation of layers of chert and shale in this formation has not yet been explained, but was probably due to alternating conditions in the sea-water which affected or interrupted the swarming of radiolarian life. The accumulation of this radiolarian ooze was stopped by a recurrence of the shallowing of the sea and the return of the shore to a line sufficiently near to insure the deposition of sands upon the siliceous deposits. These sands now form the Marin sandstone. After this sandstone had accumulated to a thickness of about 1,000 feet the subsidence of the sea-bottom, which had been in progress during the period of its deposition, caused the shore again to retreat so far that the conditions became once more favorable to marine life and another deposit of radiolarian ooze was laid down. This ooze formed the Ingleside chert. Again uplift set in, shallow water prevailed, the shore was close at hand, and the sands of the Bonita sandstone were deposited."

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[72] Loc. cit., pp. 5, 6.

These cherts would seem to be deposits made below wave-base, and although the rhythm is probably due to shiftings of currents, this in turn has doubtless a climatic cause. The rhythms are apparently, however, too numerous within a limited geological time to be due to the precessional cycle, even for the long estimates of time given by radioactivity. They suggest, therefore, the presence in the Jurassic of solar rhythms similar to those of the Pleistocene, but in a period of wide-spread equable climates.

Gilbert[73] has called attention to a notably regular alternation of strata, recurring four times in the section of the Cretaceous exposed in the basin of the Arkansas River near the Rocky Mountains. This is found in the shales of the Benton, Niobrara, and Pierre groups, totaling 3,900 feet in thickness. The pronounced rhythm is seen, however, in only a small proportion of the total thickness.

The rhythm of shale and limestone is 1.5 feet thick where the principal deposit is limestone, and repeats itself every 2.7 feet where the calcareous material suffices only to modify an otherwise argillaceous shale. Allowing a somewhat more rapid rate of accumulation for the more uniform and non-calcareous portions of the series, Gilbert takes 4 feet as an estimate for the time interval of the rhythm through the whole 3,900 feet. The only regular rhythm of sufficient length known to Gilbert at that time was the precession cycle of 21,000 years, which gives what would generally be regarded as the excessive estimate of 20,000,000 years as the length of this part of Cretaceous time.

The Tertiary rests in this region unconformably on the Pierre, but elsewhere the Fox Hills formation of sandstone and shale, 250 to 500 feet thick in the Black Hills, overlies the Pierre shale, and above the Fox Hills come the Laramie and associated formations, several thousand feet in thickness and containing unconformities. These sediments, however, were probably more rapidly accumulated. They are the record of the Laramie revolution, marked by the upthrust of mountain ranges and the downwarping of associated basins. The Dakota sandstone lies at the base of the Cretaceous, below the shale series, and varies from nothing to several hundred feet in thickness. The 3,900 feet of shale may therefore represent two-thirds or one-half of Cretaceous time, excluding the Lower Cretaceous or Comanche as a separate period. This would give 30,000,000 to 40,000,000 years as the length of the Cretaceous; but, as shown later, this accords in order of magnitude with the estimates of the whole of the Mesozoic era based on radioactivity. If the latter should prove to be sound, it appears not improbable, therefore, that Gilbert has fortunately detected running through the Cretaceous the beating of the precessional rhythm.

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[73] G. K. Gilbert: Sedimentary measurement of Cretaceous time. Jour. Geology, vol. iii, 1895, pp. 121-127.

Professor Schuchert has told the writer that when Gilbert gave this paper he and Dr. Stanton calculated that it would have taken some 6,000 years at this rate for a large Inoceramus to have become buried in sediment. As these large fossils are well preserved in many beds, showing but little solution or worm boring, it seemed at the time a strong argument against such an extravagant estimate of the length of the Cretaceous. The answer, as indicated in the preceding parts of this paper, is that the shells of living or recently dead mollusks were buried rapidly, perhaps in a single culminating storm, by a blanket of wave-stirred mud. During times of slow accumulation the successive generations of shells would be completely destroyed by boring animals, by solution, and by the recurrent wear of wave action. Thus it is characteristic of fossiliferous formations that the fossils occur in thin layers between much thicker unfossiliferous beds. Within the layer the shells are commonly well preserved, though often showing a disturbance by wave or current action. The preservation of fossils is, then, following this view, generally due to the recurrence of culminating storms at long intervals, which, stirring the bottom to unusual depths, suddenly bury a layer of organic debris beneath a protecting mantle of argillaceous or calcareous mud.

Such an action seems necessary for the preservation of fossils, even with the current estimates of geologic time. For example, let Cretaceous time be taken as 3,000,000 or 4,000,000 years in length and the burial of a large Inoceramus in the muds previously described would, with an even rate of deposition, have required 600 years. This, when tested by their state of preservation, seems to raise difficulties hardly less great than a period of 6,000 years. Generally it would be only the fixed or dead shells which would be entombed by mud blankets deposited by the exceptional storms in the stormy phase of a climatic cycle, but less frequently the deposition of sediment would be so deep and rapid that even the living members of the free bottom fauna would be smothered and buried. As an illustration may be cited the slab of Devonian sandstone described by J. M. Clarke, which shows starfishes buried while in the act of feeding on bivalve mollusks.[74]

ESTIMATES OF TOTAL TIME BASED ON OCEANIC SALTS

The use of chemical denudation as a measure of geological time began in 1876 with T. Mellard Reade. Joly[75] has carried forward this method, using the sodium chloride of the ocean, the quantity of which is known with a considerable degree of precision. The chief source of the oceanic sodium is without doubt the lime-soda feldspar of igneous rocks, from which it has been derived by the aggregate weathering and erosion of geologic time.

If the amount of sodium derived annually from igneous rocks and carried to the sea can be determined, and if it be assumed that this rate is a *true mean* for all geologic time, then the age of the ocean is obtained by simply dividing the total sodium by the annual supply. Various corrections have to be applied, however. To obtain the total sodium derived by weathering, the oceanic sodium should have added to it the amount included in the sedimentary rocks, and have subtracted from it the amount derived from juvenile waters, including the original salt, and the amount due to marine denudation. All of these corrections, however, are regarded with considerable assurance as small and would not lead to gross errors if neglected.

The amount contributed by rivers yearly to the sea has been ascertained with reasonable accuracy for representative areas by analysis of their waters. Corrections to this must be made for the amount of sodium chloride which is not derived from igneous rocks, but is borne by the wind or by man from the sea, and also that redissolved from the sedimentary rocks as sodium chloride and originating from the sea. The last correction for chloridized sodium is large and uncertain in amount.

The composition of the average igneous rock is known with fair precision. It contains between 3.4 and 3.9 per cent of soda. In suffering weathering and erosion it retains on the average between 1.3 and 1.4 per cent of its soda, this remaining in the detrital rocks. It loses between 2.10 and 2.5 per cent to the sea.

From the above it is seen that chemical denudation serves to measure the total amount of *igneous* rock which must have been eroded through geological time in order to supply the salt of the sea. Because sediments are uplifted and re-eroded, the total amount of erosion and deposition is, however, much greater than the quantity of igneous rock which has contributed to the salt of the sea. Clarke obtains a volume of igneous rock equivalent to a shell enveloping the earth and ranging from 2,050 to 1,740 feet thick as the quantity necessary to yield the sodium.

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[74] J. M. Clarke: Early adaptation in the feeding habits of starfishes. Jour. Acad. Nat. Sci., Philadelphia, 2d ser., vol. 15, 1912, pp. 113-118.

[75] Trans. Roy. Soc. Dublin (2), vol. 7, 1899, p. 23; Rept. British Asso. Adv. Sci., 1900, p. 369; Radioactivity and geology, 1909, pp. 233-251.

It is seen that chemical denudation makes possible valuable estimates of the total erosion of geological time. As a basis for attempting to measure the age of the earth, it is, however, defective only in lesser degree than the methods resting on the measurement of stratigraphic sections. Nevertheless, the method has been used as if it were very exact and conclusive. Consequently a review of the assumptions made by the several investigators on this subject should be given.

Joly assumes that the sodium derived from the sedimentary rocks, mostly as chloride from ancient sea-waters, is equivalent to that derived from similar areas of igneous rocks, so that the rate of annual supply to the sea is the same per unit from sedimentary and igneous terranes. He further assumes a constancy in the supply through all geological time. Both assumptions remove the subject from the realm of exact science to that of vague probability.

Holmes considers, on the contrary, that the evidence points to sodium being supplied by erosion of sedimentary rocks, mostly as chloride, at a higher rate than from equal areas of igneous rocks.[76] Furthermore, in regard to the rate of denudation, reasons have been shown in this article for holding that it may now be five, ten, or fifteen times higher than the mean for all geologic time. Joly, in one of his later estimates, using Murray's data, obtains an age of less than 150,000,000 years.[77] Clarke has supplanted Murray's data by more accurate calculations which reduce Joly's estimates to about 90,000,000 years.[78]

Holmes shows how, by varying the mode of using the data, quite different ages may be obtained, still under the assumption of uniform rate. If only river sodium uncombined with chlorine is used as a measure of the annual contributions from igneous rocks to the sea, an age of 180,000,000 years is obtained. Taking the mean rate of denudation as one foot in 8,600 years and the area of igneous rocks, constituting approximately 20 per cent of the drainage areas, as a measure of the new sodium contributed annually, would give an age to the oceans under the hypothesis of uniform rate of 340,000,000 years.[79] It is seen that the fundamental difficulties of the method lie, first, in the lack of knowledge as to how much of the present sodium carried to the sea is newly derived from igneous rocks; and, second, as to how the rate of supply compares now with the mean for all geologic time.

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[76] A. Holmes: The age of the earth, 1913, pp. 68-70.

[77] Radioactivity and geology, 1909, p. 247.

[78] F. W. Clarke: A preliminary study of chemical denudation. Smith. Misc. Coll., vol. 56, no. 5, 1910, p. 16.

[79] A. Holmes: The age of the earth, 1913, pp. 61-74.

The subject should not be dismissed so briefly, however, since the chief publications in American geological literature in the past 10 years on this subject have been those of Becker, and unless the validity of his assumptions is carefully examined, his arguments will appear to possess considerable force. Becker has used Clarke's data as the basis of new calculations,[80] but introduces two new assumptions into the problem. The amount of sodium in metric tons borne annually to the sea as determined by Clarke forms the basis of Becker's calculations and may be classified as follows:

10.5×10^6 = cyclic sodium, wind borne from the sea.
99.0×10^6 = chloridized sodium of sedimentary rocks.
3.0×10^6 = sodium chloridized by chlorine of igneous rocks.
62.5×10^6 = unchloridized sodium.

175.0×10^6 = total sodium annually borne to sea.

Becker's first assumption is that the *ratio* of total oceanic sodium to total oceanic chlorine, part of which is combined on precipitation with magnesium, potassium, and calcium, though partly ionized in solution, has remained the same throughout geological time. This is contrary to the expressed opinion of others, particularly A. C. Lane, who holds that the ratio of sodium to chlorine was notably less in early geological times, with the consequence that the early ocean waters were relatively rich in calcium chloride. A lesser ratio of sodium chloride to other chlorides is characteristic of the body fluids of marine as well as terrestrial animals and suggests an inheritance of their physiological processes from an early time, when in primitive animals the body fluids more nearly resembled the surrounding medium.

Becker's assumption requires that the annual amount of juvenile chlorine added to the atmosphere from volcanic sources must be equal in number of atoms to the annual supply of new sodium derived from the igneous rocks and dissolved from them mostly as bicarbonate—a postulate which appears to be against the evidence. This permits him to take 32.5×10^6 metric tons away from the 99.0×10^6 tons of chloridized sodium and regard it not as former sea salt, but as new sodium derived from igneous rocks and chloridized in the soil by atmospheric chlorine brought down as rain. As it is the contribution only of new sodium which should enter into the calculation on the age of the ocean, Becker makes up a balance sheet of this annual new sodium as follows:

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[80] G. F. Becker: The age of the earth. Smith. Misc. Coll., vol. 56, no. 6, 1910.

3.0×10^6 = sodium chloridized by chlorine of igneous rocks.
32.5×10^6 = sodium chloridized by atmospheric chlorine.
62.5×10^6 = unchloridized sodium.

98.0×10^6 = annual contribution of new sodium.

It is seen that his assumption increases the contribution of new sodium by one-half.

Becker's second assumption is that the annual rate of supply of sodium from igneous rocks to the sea has decreased through geological time according to a logarithmic curve. This is made quantitative by various secondary assumptions. He considers that the continents at the beginning had the same area as at present, and then consisted entirely of igneous rocks. The mean area of land throughout past time he takes as 0.8 of the present area and the *present* exposure of igneous rocks to lie between 0.25 and 0.3 of the mean land area. Assume that the annual contribution of sodium has diminished directly with the area of igneous rocks which has lessened in the following manner: In a certain time interval T, it is half the original area, in 2 T it is one-fourth, in 3 T it is one-eighth, in 4 T it is one-sixteenth, and so on, following the same law of decay as the loss of velocity of a body moving in a resisting medium and the decay of radioactivity. On this basis Becker derives an age of the ocean between 70,000,000 and 50,000,000 years. Of these, he prefers the higher figure. These estimates are very close to half the lengths of time obtained by using Joly's assumption of uniform rate of supply. Looking forward to a continuation of Becker's falling rate following a logarithmic curve, there will come a time, he conceives, when the erosion of new igneous rock will be negligible and the sea can never come to have more than 1.43 to 1.33 of its present salt.

In comment on Becker's method it may be said that his assumption regarding decreasing rate seems as unsafe as his other assumption regarding the constancy of composition of oceanic salts. Both Joly and Becker note the present high average elevation of the continents, but regard it as a secondary factor in the matter of rate of supply and one for which allowance need not be made. Reasons have been discussed, however, for holding that it is a major factor, which has multiplied the rate of erosion many times above what it has been during long periods of quiet marked by wide-spread shallow seas. Schuchert's paleogeographic maps show, according to Becker, that the mean area of North America above water has been eight-tenths of the present area. It may, however, have been more or less. As Schuchert recognizes, his maps minimize the limits of the epeiric seas. At times they probably extended far beyond the ascertainable bounds, since erosion of the following periods would remove the thin outlying deposits; but in the intervening stages, as Schuchert was one of the first to emphasize, the shallow seas were practically withdrawn from the continent.

The rate of erosion, however, does not turn so much on the area of land as on its elevation. During most of the Paleozoic and Mesozoic the continents stood notably low with respect to sealevel. It was particularly the mountain axes and plateaus which suffered erosion. The great Canadian Shield of older rocks stood at a low elevation and suffered but little erosion between the Proterozoic and Cenozoic—a fact first emphasized by Bell.[81] The same relations were true of other continents. Although deep geosynclines were filled with sediments and imply the destruction of great mountain ranges, their volume was small as compared to the broad areas of the continents now well above baselevel and suffering rapid denudation. Erosion could be locally rapid, but the bulk of erosion of igneous rock must have been relatively small.

Since the beginning of the Ordovician, furthermore, the actual area of igneous rocks has not diminished after an exponential law. It appears to have varied considerably with the broad covering and uncovering by sedimentary blankets, and to have been greatly increased at times by igneous extrusions. The Cenozoic has been a period of notable igneous activity, and in North America the erosion of the Cordilleran area is largely from Cenozoic extrusives and Mesozoic intrusives. The Ordovician witnessed a very wide expansion of epeiric seas and the erosion of igneous rocks was reduced to a minimum from that time forward to the Appalachian revolution. In view of these actual geological conditions the refinements of calculation introduced by Becker seem useless and lend only a false security to the results. Joly's assumption of uniform rate of denudation comes nearer to the truth; but, in view of the existence of cycles of erosion through geological time, even Joly's figure may have to be multiplied many times.

ESTIMATES OF TIME BASED ON LOSS OF PRIMAL HEAT

Before the discovery, at the opening of the twentieth century, of the wonderful field of radioactivity, it seemed to physicists that the heat lost yearly by the sun and earth was the basis of the soundest methods for determining the limits of duration of those bodies.

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[81] Robert Bell: Pre-Paleozoic decay of crystalline rocks north of Lake Huron. Bull. Geol. Soc. Am., vol. 5, 1894, pp. 357-366.

It was calculated that if the energy of the sun were derived from gravitational infall of its own mass and had been constant since the beginning, the sun could not be over 18,000,000 years old. Thomson showed, however, that the age could be extended beyond this narrow limit, but his guarded conclusion was that the sun most probably has not illuminated the earth for 100,000,000 years and almost certainly not for 500,000,000 years.

On the assumption that the temperature gradient of the earth was the result of simple cooling through geologic time from a molten beginning, Thomson calculated also the age of the earth. His first estimates were between 20,000,000 and 400,000,000 years; probably within 100,000,000 years. Later, in 1897, he reduced the time limits to between 20,000,000 and 40,000,000 years.

Clarence King, in 1893, argued from the melting curve of diabase and the temperature gradient of the earth that the earth could not possess its known tidal rigidity and be more than 24,000,000 years old. This argument rests, however, on a very nice use of very uncertain quantities. These estimates based on the thermal gradient ignore the great quantities of heat brought up by igneous activity. It is clear that the rise of Archean and later granites must have disturbed profoundly the previous temperature gradients. It has been found, furthermore, that radioactivity gives such an embarrassingly large quantity of heat that it has been necessary to assume the restriction of uranium and thorium with their observed percentage to the outer 40 miles of the earth's crust, since otherwise the earth would be heating up with geological rapidity, instead of being a body slowly cooling or in thermal equilibrium.

The discovery of radioactivity cuts out all solid basis for calculating age from the flow of solar energy or the temperature gradient of the earth. The subject of age as based on temperature gradient must still be discussed, however, because of its inherited influence on geologic thinking.

A recent attempt has been made by Becker to revive the argument from temperature gradient by including the new data of isostasy and radioactivity.[82] Becker takes the curve of fusion of diabase with respect to pressure as given by Carl Barus, a curve which is quite certainly wrong for high pressures, since Barus assumed that the fusion point increased in a *rectilinear* ratio with all pressures. Furthermore, Barus's measurement of the initial rate of rise is probably subject to considerable correction.

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[82] Age of a cooling globe in which the initial temperature increases directly as the distance from the surface. Science, vol. xxvii, 1908, pp. 227-233; also in later publications.

Becker takes next the depth of complete isostatic compensation for a uniformly distributed compensation, 114 kilometers as given by Hayford for the most probable value determined by deflections of the vertical. He argues from this that the level where the temperature gradient approaches nearest to the fusion curve of diabase is 114 kilometers.

But Hayford later changed this depth to 122 kilometers, and on the basis of measurements of intensity of gravity Bowie has recently reached 96 kilometers as the most probable value. Bowie couples this with the statement that he believes future determinations will fall between 80 and 130 kilometers.[83] This great range in the depth, as determined by the method of least squares, applied to a large mass of observational data, is owing to the wide range of the local determinations, the imperfection of isostasy, and also the imperfection of the particular hypothesis of distribution. This hypothesis assumes that the density under every topographic feature is so adjusted that at the depth of complete compensation—for example, at 114 kilometers below sealevel—every column contains the same mass, irrespective of its height. Furthermore, it assumes that the difference of densities between columns are the same at all depths down to the level of complete compensation, at which level the differences abruptly cease.

Such a simple form of hypothesis satisfies the geodetic data, giving the isostatic condition, chiefly between continents and ocean basins, as about nine-tenths complete, but a more natural assumption of variable, regional, irregular, and gradually disappearing compensation satisfies it just as well. Furthermore, a variety of evidence based on the stresses set up in the crust by the loads within it and on it indicates that the shell of greatest strength is less than a hundred kilometers thick, but that the underlying shell of weakness is very thick, with its center apparently as much as 300 to 500 kilometers in depth.[84] This is the conclusion of the writer, but there are others who hold that the data of isostasy may be so interpreted as to place the compensation even deeper and who see in the data of isostasy no evidence of weakness. It all goes to show on what an insecure and artificial foundation Becker's calculations rest. But this is only one of a series of assumptions of equal unreliability which enter into the result.

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[83] William Bowie: Investigations of gravity and isostasy. U. S. Coast and Geodetic Survey, Special Publication No. 40, 1917, p. 112.

[84] J. Barrell: The strength of the earth's crust. Journal of Geology, vols. xxii, xxiii, 1914, 1915.

The next assumption on the list is that the initial temperature gradient of the earth at the time of complete solidification was a straight line with a higher temperature at the surface than the fusion point of diabase, but with a lesser slope, intersecting the diabase curve at some distance below the surface. This primal temperature gradient is next assumed to have been modified by two factors only—some new heat of radioactive origin and a loss by conduction to the surface. Becker thus ignores, as others had done, the evidence of the recurrence on a world-wide scale of the rise of heat, manifested by batholiths and regional metamorphism—a convective overturn which would seem to have completely obscured the original temperature conditions.

By varying the initial surface temperature and the initial temperature gradient he obtains six solutions for the age of the earth and the resulting present gradient as dependent solely on cooling from the initial state. The ages range from 30,000,000 to 100,000,000 years. He chooses the 60,000,000-year earth as being most probable, as indicated by other lines of evidence. This yields a present thermal gradient from primal cooling which amounts to 77 feet for one degree Fahrenheit. As this is not far from the lower figures for the mean temperature gradient, Becker concludes that radioactivity must be a minor factor in the heat of the crust.

Thus, assumption is built on assumption into a many-storied structure and the whole rests on a foundation of quicksand. That it is a castle in the air and can not reflect the conditions of nature is indicated by various well established inferences. For example, the deeper parts of many of the older stratigraphic deposits, such as the Torridonian and Keweenawan formations and the Precambrian series of the Grand Canyon of Arizona, have been buried to a depth of several miles and are now exposed by erosion. They are not metamorphosed and therefore show that a high temperature gradient did not exist in the crust at that time except in regions of metamorphism, where plutonic igneous invasion is often indicated as the cause. Furthermore, measurements of the radium content of the siliceous rocks, and the independence of its disintergration with respect to pressure and heat, so far as laboratory experiments can ascertain, show that to depths of at least some tens of miles radioactivity must be a very important factor in determining the present temperature gradient unless uranium and thorium should have their disintegration arrested by moderate pressure; but of this there is no evidence.

Lane[85] has shown how Becker could have obtained different results by varying his postulates and points to the lack of evidence of high temperature gradients in Paleozoic and Proterozoic times.

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[85] A. C. Lane: Schaerberle, Becker, and the cooling earth. Science, vol. xxvii, 1908, pp. 589-592.

In contemplating this elaborate and ingenious argument as compared with the uncertain character of the data and the lack of agreement with significant facts, one is reminded of Huxley's well known saying, that—

> "Mathematics may be compared to a mill of exquisite workmanship, which grinds you stuff of any degree of fineness; but nevertheless what you get out depends upon what you put in; and as the finest mill in the world will not extract wheat-flour from peascods, so pages of formulæ will not get a definite result out of loose data."

PART IV.—MEASUREMENTS OF TIME BASED ON RADIOACTIVITY

OUTLINE OF THE THEORY

The detection in 1896 of the Becquerel rays given out by uranium minerals led up to the epoch-making discovery of radium. This was the opening which led to the revelation of the whole series of radioactive elements whose parents, uranium and thorium, have the highest atomic weights of all known elements. Each of these parental elements slowly and regularly breaks down into a descendent series. In so doing they liberate α, β, and γ-rays which enable the process of disintegration to be detected and constitute the radiations discovered by Becquerel. The α-rays are positively charged atoms of helium, shot out of the parent atoms with enormous velocities. The β-rays are negatively charged electrons, having a mass of about 1/1,250 that of a hydrogen atom, and expelled even more swiftly than the α-particles. γ-rays are not material particles in rapid motion, but appear to be of the same nature as X- or Röntgen-rays.

Confining attention to the uranium series, the evidence indicates that eight successive ejections of helium atoms, separated by other and intermediate β and γ changes, result in the making of lead out of uranium. The atomic weight of helium being 4.0 and uranium 238.2, it follows that the atomic weight of lead derived from uranium should be 206.2.

In the enormous number of atoms which exist in even a chemical trace of a radioactive substance, a few pass each second into a condition of instability and, by ejecting either an α or β particle, pass into another atomic state. The number of atoms is so great that, as in the kinetic theory of gases, the law of averages strictly applies. In the successive products from uranium down to lead various degrees of stability are shown, the more stable atom enduring on the average a longer time before it passes into a configuration of internal instability and as a result breaks down. From the degrees of radioactivity and the rate of decay of the radioactivity of each substance the relative instabilities may be measured and these may be translated into the length of time when half of the given substance will have been transformed. This is known as the half-value period. For example, let a certain weight of radium be designated as 64 A. In 1,660 years it will have been half transformed into descendent elements and 32 A will remain as radium. In 1,660 years more, or 3,320 years from the beginning, half of this will have been transformed and the quantity of radium will be 16 A. In another 1,660 years 8 A will remain. Thus in 9,960 years an initial quantity of 64 A will be reduced to A. It is clear, then, that the parent element, uranium, exists in the earth's crust only because its half-value period is enormously long—long even in comparison with the geologic eras.

There are at present listed fifteen members and a couple of branch variations in the uranium series, beginning with uranium and ending with lead. Several of these are not chemically separable from certain other elements and are known as isotopes. The half-value periods of representative members in the order of their genesis are given by Rutherford[86] as follows:

Uranium	6×10^9 years
Ionium	greater than 20,000 years
Radium	2,000 years
Radium emanation	3.75 days
Radium D	16.5 years
Radium F	136 days
Lead	stable

Recent determinations by Ellen Gleditsch of a high order of precision have shown the half-value period of radium to be about 1,660 years.[87] Professor Boltwood, in whose laboratory this work was done, regards the error of this mean as probably not more than 2 per cent. The half-value period of uranium is decreased correspondingly.

In a uranium mineral all of the descendent elements are present, and after about a million years a state of equilibrium is reached, after which time each decays at the same rate at which it is generated. It follows that after this a constant ratio is maintained between each, the relative amounts being determined by the rates of decay. Thus, in a uranium mineral, radium occurs to the amount of about 1 part to 3,125,000 parts of uranium. These radioactive substances exist consequently in such small amounts that they are insensible in gravimetric analysis, but through their radioactive properties, the electroscope and the fluorescent screen enable the investigator to identify the substances and even to count the atoms which disintegrate. As a result, the half-value period of radium may be determined by comparison with that of the radium emanation, and uranium by comparison with radium, as well as by other ways. Thus the accuracy with which the rates of decay can be measured, the agreement by different methods, and the great duration of uranium unite to fit the series to serve as a measure of geological time.

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[86] E. Rutherford: Radioactive substances and their transformations, 1913, p. 24.

[87] Ellen Gleditsch: The life of radium. Am. Jour. Sci., vol. 41, 1916, pp. 112-124.

The rate of decay is not affected by the nature of chemical combination or physical state. Temperatures up to 2,500° C. and pressures up to 160 tons per square inch have been found not to influence the rate of decay of the products of radium. It is highly probable but not as yet actually demonstrated that uranium is similarly unaffected. Thus the atoms of uranium break up with a uniform rate whether they are in elemental form or combined in a salt; whether they are in solid, liquid, or gas. Of course there must be conditions under which an element which is now breaking down was built up, but such a physical environment would appear to be so extreme that it must occur under unknown cosmic conditions, and there is no reason to expect the modification of disintegration rates in the outer crust of the earth, a region in which temperatures and pressures are both relatively low.

The uranium minerals are commonly found associated with pegmatite dikes. Since the time of their growth their temperatures have been well below the crystallization temperature of granite and the pressures have diminished with the progress of erosion from an initial maximum of possibly twenty or thirty thousand pounds per square inch to atmospheric pressures as they are exposed at the surface. From the time radioactivity attained equilibrium in the uranium or thorium mineral, the end products have been accumulating within it consequently at a uniform rate. These in a dense crystalline rock are not removed unless the minerals are subjected to passing solvents, which would then surely record their effects by the alteration of the mineral itself. An atom of uranium which breaks up will ultimately give rise as stable products to eight atoms of helium and one atom of lead. If the quantity of these can be measured and compared with the quantity of uranium in the same volume of material, data are obtained for measuring the age of the mineral and with it the age of the rock formation of which it is a part.

Following this introduction, the methods of measuring the earth's age by radioactive processes and the results which have been attained may be considered in more detail. For this purpose the best presentation will be to quote freely from a recent article by Arthur Holmes,[88] who by his research has contributed much to this subject. The following three topics are quoted entire, as they give in brief space the essentials of the methods and the original article will be seen by but few American geologists. The importance of the whole subject from a geological standpoint is such that this presentation should be given in an American geological publication.

ACCUMULATION OF HELIUM [89]

The proof is complete that helium is a stable product of the decay of both uranium and thorium. It is always present in radioactive minerals. In 1903 Ramsay and Soddy demonstrated its genesis directly from radium emanation. In 1910 Strutt went further and measured its rate of formation in pitchblende and thorianite. His results show that one gram of uranium[90] generates helium at the rate of 1 cc. in 10 million years, and that one gram of thorium[90] generates helium at the rate 1 cc. in 30 million years. These figures have been verified quite independently by directly *counting* the α-particles—helium atoms—emitted by various members of the radioactive families. Strutt found that the thorianite which he used in his experiments originally contained 280,000,000 times more helium than the amount which the same mineral could generate in a year. The inference is clear. That large volume of helium must have taken 280,000,000 years to accumulate.

Before going a step further and asserting that this is also the *age* of the mineral, two questions must be asked and answered:

(*a*) Was there any helium present in the mineral at the time of its crystallization, or has it been generated since?

(*b*) Can we be sure that no helium has escaped from the mineral during the period which has elapsed since its crystallization?

In the first case it is only necessary to notice that ordinary rocks and minerals contain only the slightest traces of helium, and that what little there is can be fully explained by the small quantities of the radioelements which are always present. If any strongly radioactive mineral in an igneous rock did contain a little helium as an original impurity, its amount would soon become negligible in proportion to the large quantities subsequently generated.

The second question is not so easily disposed of. It has been experimentally demonstrated that as soon as a mineral is exposed to the air it begins to lose its helium. When it is powdered for analysis, still more leaks away. Consequently the helium now found in a mineral can only be a part, rarely as much as one-half, of the total amount which has been generated within it during its lifetime. This must be carefully remembered in interpreting the helium contents of minerals.

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[88] Radioactivity and the measurement of geological time. Proc. of the Geologists' Asso., vol. xxvi, part 5, 1915, pp. 289-309. The following three topics are quoted from pp. 294-300, 303-309, with some omissions.

[89] By Arthur Holmes.

[90] When in equilibrium with all its daughter elements.

Returning to our thorianite, it will now be clear that it would be erroneous to suppose that its age is only 280,000,000 years. Its age must be much greater than that. Thorianite occurs in Ceylon in sands and gravels, where it has been exposed to the action of the weather for thousands of years—ever since it was broken away from its original home in

TABLE A

Geological period.	Mineral.	Locality.	Helium ratio.[91]	Millions of years.
Recent..........	Zircon.......	Mount Somma	<0.01	0.1
Pleistocene......	Zircon.......	Mayen, Eifel	0.09	1.0
Pliocene.........	Zircon.......	Campbell Island, New Zealand.	0.223	2.5
Miocene.........	Zircon.......	Expailly, Auvergne	0.57	6.3
Oligocene........	Siderite.....	Niederpleis, Rhine Provinces.	0.76	8.4
Post-Eocene......	Hæmatite....	County Antrim	2.8	30.8
Permian?........	Zircon.......	Northeast Tasmania.	3.88	42.7
Upper Carboniferous.	Limonite....	Forest of Dean...	13.3	146 (320)[92]
Carboniferous to Cambrian.	Zircon.......	Green River, North Carolina.	13.4	147 (330)
Devonian........	Zircon.......	Brevig, Norway...	4.94	54 (380)
Devonian........	Hæmatite....	Caen	13.2	145
Upper Precambrian.	Zircon.......	Cheyenne Canyon, Colorado.	12.8	141
Upper Precambrian.	Zircon.......	Miask, Urals.......	19.0	209
Upper Precambrian.	Zircon.......	Ceylon	26.0	286
Upper Precambrian. (?)	Thorianite...	Ceylon	27.9	307
Middle Precambrian.	Sphene......	Arendal, Norway...	36.8	405 (1,200)
Middle Precambrian.	Sphene......	Twedestrand, Norway.	40.8	449 (1,200)
Lower Precambrian.	Zircon.......	Renfrew County, Ontario, Canada.	56.6	623
Lower Precambrian.	Sphene......	Renfrew County, Ontario, Canada.	65.0	715 (1,500)

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[91] The ratio of helium in cubic centimeters to an amount of uranium (U) equivalent in its rate of helium generation to that of the uranium and thorium present in the mineral. Age = He/U × 11 million years.

[92] The figures in parentheses represent the age in millions of years based on lead ratios for the corresponding periods.

the pegmatite dikes of that island. During all that time its store of helium has been leaking away, and present measurements give only a *minimum* estimate of its age.

In the course of his work Strutt investigated phosphatic nodules and iron ores from sedimentary rocks, and zircons and sphenes from igneous rocks, the two latter being among the most radioactive of the commoner rock-forming minerals. The results for iron ores and zircons are the most valuable and instructive, for they represent widely different periods, and they show that, in spite of the unavoidable leakage, the older minerals contain far more helium than the younger ones.

In Table A some of the highest of the ages based on Strutt's results are given for each of the geological periods represented. It will be seen that with few exceptions they stand in close relation to the geological ages of the minerals. For comparison, the corresponding ages based on the accumulation of lead are given in parentheses in the cases where these have been measured. The figures clearly bring out the limitations of the helium method. All that it can tell us is that the age of a mineral is greater than a certain minimum value.

PLEOCHROIC HALOS[93]

The presence of uranium and thorium in rocks is sometimes revealed in a most beautiful way. When mica and tourmaline and a few other minerals are examined in thin sections under the microscope, small circular spots, known as pleochroic halos, are sometimes seen. At the center a minute crystal of zircon, or of some other radioactive mineral, can usually be detected. In 1907 Joly demonstrated beyond doubt that these intensely pleochroic spots were due to the radioactivity of the tiny inclusions at their centers.

The α-rays, or helium atoms, discharged from the different radio-elements have not all the same velocity. Those from uranium can penetrate about an inch of air, and they give up most of their electrical charge just before coming to rest. Since they must be discharged equally in all directions, they come to occupy a spherical surface around the central uranium. The helium atoms from radium travel more rapidly and thus penetrate farther, forming another spherical surface. Those from radium C have the maximum range and form a sphere which incloses all the others. The ranges of the helium atoms from the thorium family are of the same order, but slightly greater than those from the uranium family, and consequently the resultant spheres are of somewhat greater diameter.

The distance to which a helium atom can penetrate depends on the density of the matter through which it is passing. The ranges in air have been carefully measured, and the corresponding values for biotite can easily be calculated. The largest sphere from the uranium family should have a diameter of 1/30 mm., and that from the thorium family a diameter of 1/25 mm. Now the maximum diameters of halos have been carefully measured, and surely enough there are two types of halos with exactly the diameters theoretically to be expected. Clinching the argument by practical demonstration, Rutherford has made artificial halos in glass and in flakes of biotite.

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[93] By Arthur Holmes.

The color of a halo depends on two factors: (*a*) the radioactivity of the central inclusion, and (*b*) the age of the mineral in which it occurs. As the helium atoms accumulate in their spherical shells the color gradually deepens. It is interesting and significant to notice that halos are found only in fairly old rocks. Granites of Tertiary age are practically free from perceptible halos, whereas in biotite granites of Permian and Devonian age they are frequently well developed.

Recently Joly and Rutherford have attempted to estimate the age of the biotite halos in the Leinster Granite of County Carlow (Lower Devonian) by means of their color. Artificial halos were made in the same biotite under controlled conditions which made it possible to measure accurately both the *radioactivity* and the *time* for which it acted. Artificial halos are made with a high degree of radioactivity acting for a short time. Natural halos are made with a low degree of radioactivity acting for a long time. Suppose that a natural halo is found with exactly the same depth of color as an artificial one. If, now, the radioactivity of the central inclusion can be estimated, then the *time* for which it must have acted can easily be calculated. The period of time so found would, of course, be a measure of the age of the halo and of the mineral in which it had developed. Once the natural halo has been matched in color with an artificial halo, the only problem that remains is the estimation of the radioactivity of the zircon at the center of the natural halo.

The volume of the inclusion can be determined by working with a high-power microscope. Unfortunately it is impossible to separate the zircons and measure their uranium contents directly. The difficulty is surmounted by an appeal to probable limits. No zircons are known to contain more than 10 per cent of uranium. If this figure is employed throughout for all the halos examined, some of them, the paler ones, will give ages that are obviously too low, while others, the darker ones, will give ages that approach the correct figure, and may perhaps even exceed it. The values actually arrived at by Joly and Rutherford varied between 50 and 470 million years, the larger figure being certainly nearer the truth than the smaller one. Whether it is too high or too low can not as yet be determined by the method of attack pursued in this investigation.

ACCUMULATION OF LEAD[94]

Discussion of the evidence.—The suggestion that lead is the final product of the uranium family was made by Boltwood in 1905. All the evidence which has become available since that date convincingly upholds the correctness of his view, which from the first was much more than a mere guess or assumption. Up to the present the generation of lead from a radioactive preparation has not been directly demonstrated, but the reason is not far to seek. Such a preparation, originally free from spectroscopic traces of lead, would require many years to generate within itself a perceptible accumulation of lead. Two or three experiments were begun a few years ago with this end in view, but more time must elapse before there can be any hope of detecting the final product. The following lines of deductive evidence, however, leave no room for doubt that the final product really is chemically identical with lead:

(*a*) When the radio-elements are arranged in their proper positions in the periodic classification, the final product of uranium naturally falls into the division already occupied by lead.

(*b*) The atomic weight of ordinary lead is 207.1 (International, 1915), or 207.19 according to Baxter, Thorvaldsen, and Grover (1915). However, according to the data previously given, the atomic weight of the final product should be 206.2, or 206 according to Hönigschmid's measurement of the atomic weight of radium. This was for some years a source of difficulty, but it has now led to the discovery that lead which has accumulated in radioactive minerals, and which is recognized as lead by its chemical and spectroscopic behavior, has actually a lower atomic weight than that of ordinary lead. Richards and Lembert in America, Maurice Curie in France, and Hönigschmid in Austria have investigated lead prepared from pitchblende and other uranium minerals, and the values of the atomic weight found by them range from 206 to 206.5.[95] The higher values are all from pitchblendes of secondary origin, which are liable to contamination with ordinary lead, owing to their association with galena. The lowest values are from pure uraninite (German East Africa) and from a similar mineral, Bröggerite (Norway), both of which were fresh primary minerals quite free from traces of galena. Atomic weight evidence, therefore, strongly supports the view that the final product of uranium is an isotopic variety of lead.

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[94] By Arthur Holmes.

[95] For references and a table of results see Holmes and Lawson: Phil. Mag., vol. xxix, 1915, p. 682.

(*c*) It is found that in fresh, primary, uranium-bearing minerals of the same geological age the amount of lead is closely proportional to that of uranium—that is to say, the ratio Pb/U (referred to as the *lead ratio*) is practically constant. For each gram of uranium in a mineral the amount of lead generated and accumulated is the same as in any other mineral of equal antiquity, always provided that no lead has been lost or gained from external sources during the period concerned.

(*d*) When series of minerals of different ages are compared it is found that the lead ratios vary in sympathy with those ages. The older the mineral the higher is the lead ratio.

The rate at which lead is generated from uranium can easily be calculated. The rate of production of helium is accurately known, and the mass of lead set free in the same time is roughly 6.5 times that of the helium liberated. In a year one gram of uranium generates 1.25×10^{-10} grams of lead, and at this rate one gram of lead would be produced in 8,000 million years.[96] If a mineral contains a percentage of accumulated lead of radioactive origin represented by Pb, and a percentage of uranium represented by U, then the *age* of the mineral is given approximately[97] by the expression:

$$\frac{\text{Pb}}{\text{U}} \times 8{,}000 \text{ million years (or, using the latter value,}$$

$$\frac{\text{Pb}}{\text{U}} \times 7{,}500 \text{ million years.—J. B.).}$$

Before applying this method to the actual measurement of geological time, it is necessary to examine closely a number of assumptions which are implied. It is clear that if any lead should have been originally present in a radioactive mineral at the time of its genesis, a serious difficulty will have arisen. In all the ordinary minerals of igneous rocks, lead is a negligible quantity. The difficulty may often be overridden by analyzing only those minerals which are much richer in uranium than the main body of the rock. Within them, lead will steadily accumulate, and any original lead will, as time goes on, become of less and less importance in proportion to the whole. The difficulty is not, however, wholly dispelled in this simple way. If original lead were to be present in troublesome quantities the amount is likely to vary from mineral to mineral, and the lead ratios will lack that constancy which is the criterion of their value. Moreover, the lead from such minerals is of two kinds—"ordinary" lead and "uranium" lead—distinguishable by their atomic weights, though not by chemical methods of analysis. If the lead is wholly original its atomic weight should be about 207.1; if generated from uranium the atomic weight should be about 206.2. Values between these figures imply a mixture of the two types. The criteria pointing to the absence of original lead in perceptible quantities are (*a*) constancy of the lead ratios in a series of fresh, primary minerals of the same geological age, and (*b*) an atomic weight value of the order 206.2.

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[96] NOTE BY J. B.—The newer and more accurate determinations of the half-value period of radium and the ratio between the amounts of radium and uranium reduce this 8,000 million years to 7,500 million, as calculated for the writer by Professor Boltwood. This is the hitherto unpublished mean of various determinations by Boltwood and others. All the calculations by Holmes have been supplemented by the writer, according to this new value, by the addition of a correction in parenthesis which is .9375 of the old value. The results are given, however, to only two or three significant figures.

[97] See footnote 98.

In cases where the lead ratios are not constant, or where the atomic weight is too high, the presence of original lead is to be suspected and the ratios become worthless as an index of age. The thorium minerals from Ceylon afford an instructive instance.[98]

We may now proceed to consider a number of analyses of minerals which may fairly be used for the measurement of geological time. In Table E many of the analyses compiled by Boltwood in 1907 are quoted, together with several new ones which have since become available.

I. The uraninite of Glastonbury, Connecticut, United States of America, occurs in pegmatite dikes which are associated with a granite probably of late Carboniferous age. The granite intrudes Lower Carboniferous strata and is certainly pre-Triassic.

III. Unfortunately, uraninite does not occur in the Devonian igneous rocks of the Christiania district of Norway. As has been already shown, analyses of thorite are far from reliable as tests of age, and the writer has felt reluctantly obliged to abandon them from that point of view. The remaining analyses give ratios varying from 0.04 to 0.062, the discrepancies being here due to the difficulty of accurately determining small quantities of lead. The average age given in the table may be too high, and must be regarded as indicating no more than an approximation to the correct figure. It is significant that the somewhat older granites of County Carlow give a maximum age of 470,000,000 years as determined by the pleochroic halo method.

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[98] Since the amount of uranium present is slowly decreasing as the helium and lead accumulate, it is clear that the amount of uranium U_0 originally in the mineral must have been greater than the amount of U now present. For periods of time less than 2,000 million years, the average amount of uranium present in a mineral throughout its history—the time average—is almost exactly $(U_0 + U)/2$. Now U_0 is given by $U + Pb + He$, or by $U + 1.15\ Pb$. Consequently $(U_0 + U)/2 = U + 0.575\ Pb$, and a more accurate expression of the age of a mineral than that given above is $\frac{Pb}{U + 0.575\ Pb} \times 8{,}000$ million years. $\left(\frac{Pb}{U + 0.575\ Pb} \times 7{,}500\right.$ million years.—J. B.$\left.\right)$

TABLE E

I

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Uraninite	Glastonbury, Connecticut, U. S. A.	2.9	70	0.041	Hillebrand.
Uraninite	Glastonbury, Connecticut, U. S. A.	3.0	70	0.043	Hillebrand.
Uraninite	Glastonbury, Connecticut, U. S. A.	2.8	70	0.040	Hillebrand.
Uraninite	Glastonbury, Connecticut, U. S. A.	3.0	72	0.042	Hillebrand.
Uraninite	Glastonbury, Connecticut, U. S. A.	2.9	72	0.040	Hillebrand.

Geological age: Carboniferous.
Average age[99] from lead ratios: 320,000,000 years. (300,000,000 years.—J. B.)

[99] Calculated in each case from the formula $\frac{\text{Pb}}{\text{U} + 0.575\ \text{Pb}} \times 8{,}000{,}000{,}000$ years.

II

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Uraninite	Spruce Pine	3.9	77	0.051	Hillebrand.[100]
Uraninite	North Carolina	4.2	77	0.055	Hillebrand.
Uraninite	North Carolina	3.3	67	0.049	Boltwood.[100]
Uraninite	Marietta, South Carolina	3.3	71	0.046	Hillebrand.
Zircon	North Carolina	0.0036	0.076	0.047	Holmes.[101]
Zircon	North Carolina	0.0055	0.130	0.042	Holmes.

Geological age: Cambrian to Carboniferous.
Average age from lead ratios: 370,000,000 years. (345,000,000 years.—J. B.)
(Corrected for primary lead:) 330,000,000 years. (310,000,000 years.—J. B.)

[100] Atomic weight of lead (Richards and Lembert, 1914), 206.4. This suggests that 20 per cent of the lead may be primary.

[101] "The Age of the Earth," p. 160 (1913).

III

Minerals.	Locality.	Lead.	Uranium.	Pb/U	Analyst.
Zircon	Brevig, Christiania district, Norway	0.037	0.931	0.040	Holmes.
Homelite	Brevig, Christiania district, Norway	0.012	0.244	0.050	Holmes.
Zircon	Brevig, Christiania district, Norway	0.009	0.194	0.046	Holmes.
Pyrochlore	Brevig, Christiania district, Norway	0.012	0.192	0.062	Holmes.
Pyrochlore	Brevig, Christiania district, Norway	0.009	0.186	0.048	Holmes.
Biotite	Brevig, Christiania district, Norway	0.007	0.160	0.044	Holmes.
Zircon	Brevig, Christiania district, Norway	0.006	0.146	0.041	Holmes.
Tritomite	Brevig, Christiania district, Norway	0.003	0.063	0.048	Holmes.
Freyalite	Brevig, Christiania district, Norway	0.003	0.053	0.056	Holmes.
Mosandrite	Brevig, Christiania district, Norway	0.002	0.043	0.047	Holmes.
Aegirine	Brevig, Christiania district, Norway	0.0025	0.015	0.060	Holmes.
Eucolite	Brevig, Christiania district, Norway	0.001	0.017	0.059	Holmes.

Geological age: Devonian (probably Lower or Middle).
Average age from lead ratios: 380,000,000 years. (355,000,000 years.—J. B.)

IV

Minerals.	Locality.	Lead.	Uranium.	Pb/U	Analyst.
Uraninite	Anneröd, Norway	8.4	66	0.13	Hillebrand.
Uraninite	Anneröd, Norway	7.8	68	0.12	Blomstrand.
Annerödite	Anneröd, Norway	2.2	15	0.15	Blomstrand.
Uraninite	Elvestad, Norway	9.3	66	0.14	Hillebrand.
Uraninite	Elvestad, Norway	8.0	57	0.14	Hillebrand.
Uraninite	Skaartorp, Norway	8.8	65	0.135	Hillebrand.
Uraninite	Huggenäskilen, Norway	8.8	68	0.13	Hillebrand.
Uraninite	Huggenäskilen, Norway	9.0	76	0.12	Lorenzen.
Thorite	Hittero, Norway	1.2	8.2	0.15	Lindström.
Bröggerite	Norway	8.61	67.4	0.13	Hofmann.[102]
Bröggerite	Norway	8.49	67	0.13	Hofmann.

Geological age: Middle Precambrian (pre-Jatulian).
Average age from lead ratios: 1,000,000,000 years. (940,000,000 years.—J. B.)

[102] Ber. d. d. Chem. Ges., vol. xxxiv, p. 914 (1901). Atomic weight of lead (Hönigschmid, 1914), 206.06.

V

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Uraninite	Arendal, Norway	9.8	56	0.18	Hillebrand.
Uraninite	Arendal, Norway	10.2	61	0.17	Hillebrand.
Uraninite	Arendal, Norway	9.4	56	0.17	Lindström.
Thorite	Arendal, Norway	1.5	9	0.17	Nordenskiöld.
Orangite	Landbo, Norway	1.2	7.5	0.16	Hidden.
Xenotime	Naresto, Norway	0.62	2.9	0.21	Blomstrand.

Geological age: Middle Precambrian (pre-Jatulian).
Average age from lead ratios: 1,200,000,000 years. (1,120,000,000 years.—J. B.)

VI

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Fergusonite	Ytterby, Sweden	0.18	1.06	0.17	Holmes.
Gadolinite	Ytterby, Sweden	0.36	2.41	0.15	Holmes.

Geological age: Middle Precambrian (Ser-archean granites).
Average age from lead ratios: 1,100,000,000 years. (1,030,000,000 years.—J. B.)

VII

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Uraninite	Villeneuve, Quebec, Ontario	10.14	60	0.17	Hillebrand.

Geological age: Middle Precambrian.
Age from lead ratio: 1,200,000,000 years. (1,120,000,000 years.—J. B.)

VIII

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Uraninite..................	Morogoro, German East Africa...............	6.98	74.54	0.094	Marckwald.*
Uraninite..................	Morogoro, German East Africa...............	6.88	74.72	0.092	Marckwald.

Geological age: Undetermined, but younger than IX and X.
Average age from lead ratios: 700,000,000 years. (655,000,000 years.—J. B.)

* Atomic weight of lead (Hönigschmid, 1915), 206.04.

IX

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Zircon.....................	Nrassi Basin, Mozambique...................	0.032	0.193	0.17	Holmes.
Zircon.....................	Monapo River, Mozambique..................	0.026	0.171	0.15	Holmes.
Biotite....................	Ligonia, Zambesia..........................	0.014	0.097	0.14	Holmes.

Geological age: Undetermined, but younger than X.
Average age from lead ratios: 1,100,000,000 years. (1,030,000,000 years.—J. B.)

X

Minerals.	Locality.	Lead.	Uranium.	Pb/U.	Analyst.
Zircon.....................	Mozambique...............................	0.054	0.257	0.21	Holmes.

Geological age: Undetermined: Oldest gneissose granites.
Age from lead ratio: 1,500,000,000 years. (1,400,000,000 years.—J. B.)

IV. Turning to the Precambrian rocks of Scandinavia, there are three series of igneous intrusions containing radioactive minerals. All are intrusive into the older schists and quartzites of the Precambrian, and all were worn down by the denudation which prepared the platform on which the Jatulian formations were laid down. They all, therefore, belong to the middle division of Precambrian time. The position of these rocks in the Precambrian sequence will be made clear by the following tentative classification:

	Fenno-Scandia	Canada
UPPER PRECAMBRIAN or EP-ARCHEAN	*Rapakivi granite*	
	Jotnian	Keweenawan
	∼∼∼∼∼∼∼∼∼	∼∼∼∼∼∼∼∼∼
	Jatulian	Animikie
Ep-Archean interval	∼∼∼∼∼∼∼∼∼	∼∼∼∼∼∼∼∼∼
MIDDLE PRECAMBRIAN or MES-ARCHEAN	*Ser-archean and post Kalevian granites*	*Algoman and post Huronian granites*
	Upper Kalevian	Upper Huronian
	∼∼∼∼∼∼∼∼∼	∼∼∼∼∼∼∼∼∼
	Lower Kalevian	Lower Huronian
	∼∼∼∼∼∼∼∼∼	∼∼∼∼∼∼∼∼∼
	Post Bottnian granites	*Granite intrusions*
	Bottnian	Sudburyan
Epi-Laurentian interval	∼∼∼∼∼∼∼∼∼	∼∼∼∼∼∼∼∼∼
LOWER PRECAMBRIAN or PROT-ARCHEAN	*Post-Ladogian granite*	*Laurentian granites*
	Ladogian	Grenville series Keewatin series Coutchiching series

The first group of minerals—from the Moss district of south Norway—belongs to pegmatites associated with granites of post-Kalevian age. The lead ratios only vary from 0.12 to 0.15 and the atomic weight of lead from Bröggerite (lead ratio = 0.13) was found by Hönigschmid to be 206.06. Here, then, all the criteria of a thoroughly satisfactory series of minerals are fulfilled, and the age assigned to the rocks may be accepted with confidence.

V. A similar suite of minerals is found in the pegmatites of the Arendal district of south Norway. In this case the associated granites may be post-Kalevian or post-Bottnian. The agreement of the lead ratios is good except for the abnormal value given by Xenotime. (It is to be noted, however, that the per cent of lead in this mineral is only 0.62, which indicates that but relatively little weight should be attached to the analysis.—J. B.)

VI. Although many analyses have been made of minerals from the famous pegmatites of Ytterby (Ser-archean granites) no determinations of lead have hitherto been published. Two analyses by the writer indicate that the minerals are of the same order of age as those of the two preceding groups. Geologically the Ser-archean and post-Kalevian granites can not be distinguished in time, and as far as correlation has been attempted they have been grouped together.

VII. A valuable analysis of a Canadian Middle Precambrian mineral is that of the uraninite from Villeneuve, in Ontario. The writer is indebted to the Canadian Geological Survey for the information (due to the work of Mr. M. E. Wilson) that the pegmatite in which the uraninite occurs is associated with a granite which (*a*) is intrusive into the Grenville series and into the pyroxene granites which penetrate the Grenville series, and (*b*) is intruded by diabase dikes of Keweenawan age. These details make it clear that the pegmatite belongs to one of the periods of granite intrusions contained within the Middle Precambrian of the above classification. This conclusion is completely in harmony with the age deduced from the single analysis available.

Conclusions on accumulation of lead[103]—1. The method of determining geological time by the lead ratios of radioactive minerals gives results consistent among themselves and in harmony with geological evidence, wherever this is clear. Rejecting minerals in which alteration, or the presence of primary lead, has vitiated the results in advance, the evidence is conclusive that the ratio Pb/U is nearly constant for minerals of the same age, and that the value of the ratio increases as the geological age of the respective minerals increases.

2. The results are in keeping with those deduced from other radioactive methods.

3. The age of the Carboniferous and Devonian intrusions is of the order of 300 to 400 million years; the age of the granite intrusions of the Middle Precambrian is of the order 1,000 to 1,200 million years.

4. Where geological evidence is obscure, as, for example, in the Appalachians of the Carolinas, the method is capable (when suitable minerals are present) of being applied to the determination of the age of granite and similar intrusive rocks.

5. The method may be used comparatively for the correlation of igneous intrusions in various parts of the world, and in particular for the correlation of the Precambrian rocks.

6. Note added November 8, 1915.—In an address to the Geological Society of America (Bull. 26, p. 171, 1915), G. F. Becker has attempted to correlate recent developments in radiogeology and isostasy. He assumes that Hayford's level of isostatic compensation, at a depth of 121 km., is the depth of easiest fusion—that is, the depth at which the cooling curve most nearly approaches the curve of fusion. On this assumption

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[103] By Arthur Holmes.

he finds that radioactivity maintains only one-seventh of the present gradient, and that the age of the cooling earth is 68,000,000 years. With the data he uses it is calculated that if two-thirds of the gradient is maintained by radioactivity, then the age becomes 1,314,000,000 years, and the depth of easiest fusion becomes 300 km. In a series of papers running through the Journal of Geology, 1914 and 1915, J. Barrell has shown that the zone of easiest fusion must be below the level of compensation, and from considerations based on the strength of the earth's crust and on tidal phenomena, he places the source of igneous activity at about the middle of the Asthenosphere—that is, at a depth of 350-500 km. Combining this conclusion with Becker's analysis, it is easily seen that the age of the cooling earth is not 68,000,000 years, but considerably greater than 1,314,000,000 years.—A. H.

PART V.—THE AGE OF THE LLANO SERIES, TEXAS

PREVIOUS OPINIONS

A discussion of the age of the pegmatites which intrude the Llano series of Precambrian sediments would be out of place in an article of this general character if it were merely to settle a disputed point in regard to local geology, but it happens that Becker has used the uranium minerals of the pegmatites in this series in an argument which completely discounts the value of the uranium-lead ratio as a means of determining the age of a uranium mineral.[104] Becker's conclusions are so adverse and apparently so final to one not otherwise familiar with the subject that they may in part account for the lack of further papers treating of the subject in American geological journals since Boltwood's publication in 1907. In England, on the contrary, considerable work has been done. In regard to the radioactive minerals of the Llano series, however, Holmes, relying in part on Becker's statements regarding their age and the variations in the lead-uranium ratios, discusses them as a warning example of the effects of alteration in minerals subsequent to their origin. Holmes takes this position, since, as seen, he holds that for many localities such minerals do give valuable indications of age. The present re-examination of the data goes to show, however, that these minerals of the Llano pegmatites do give definite and accordant measures of age when they are properly interpreted. So many differences arise between the views of Becker and the present writer in the analysis of this subject that, as a basis for discussion, Becker's statements must be quoted as an introduction to the topic. Under the subheading of "Radioactivity and the Earth's Age," Becker states:

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[104] Relations of radioactivity to cosmogony and geology. Bull. Geol. Soc. Am., vol. 19, 1908, pp. 113-146.

"Now from the helium found in an analysis of fergusonite by Messrs. Ramsay and Travers, Mr. Rutherford[105] computes an age of at least 500 million years, and from an uranium mineral at Glastonbury, Connecticut, analyzed by Mr. Hillebrand, a similar antiquity. The Glastonbury granite gneiss is equivalent to the Wilbraham gneiss of Mr. Emerson,[106] who pronounces it unequivocally early Cambrian. Messrs. Rice and Gregory[107] feel some uncertainty as to its age, but do not suggest a new position for it. For the present purpose, it is sufficient to regard it as at the bottom of the Cambrian. Mr. Walcott's estimate of the lapse of time since the beginning of the Cambrian is nearly 28 million years, or about an eighteenth part of that suggested by Mr. Rutherford.

"Mr. Boltwood[108] has computed the age of a large number of uranium minerals from their lead content. He shows that according to theory the age will be given in years to a first approximation, if the ratio of metallic lead to metallic uranium is multiplied by 10 million. In this way he gets for the age of the Glastonbury minerals 410 million years. Now, at Barringer Hill, in Llano County, Texas, there is a very remarkable deposit of rare radioactive minerals, which are so abundant that they have been mined for the use of an electric lighting company. It happens that the age of the granite in which the pegmatite occurs is known. Mr. Walcott[109] discovered in this county his Llano group, which belongs to the Grand Canyon series, not far below the Cambrian. The granites are intrusive in these sediments. The great masses of granite which occur in western Burnet and all through Llano County belong to the same age as the strata, and Mr. Walcott is careful to remark that he did not observe any rocks of undoubted Archean age in the region. A number of analyses[110] of the rare minerals of Barringer Hill are available, and by Mr. Boltwood's rule they give the following ages for the Llano beds:

	Million years
Yttrialite, J. B. Mackintosh	11,470
Yttrialite, W. F. Hillebrand	5,136
Mackintoshite, W. F. Hillebrand	3,894
Nivenite, Mackintosh	1,671
Fergusonite, Mackintosh	10,350
Fergusonite, Mackintosh	2,967

"Mr. Boltwood informs me, however, that, with the possible exception of nivenite, none of these minerals is really suitable for throwing any definite light on the question of the uranium-lead ratio for Llano County, since all of the specimens show signs of incipient or advanced alteration; but, according to theory, the state of combination is without influence on radioactivity, so that the only alterations which would affect the matter must involve the addition or abstraction of uranium or lead, and mere hydration, for example, should be without effect. The nivenite, interpreted by the rule, indicates an age fifty times as great as seems admissible from a geological standpoint and four times as great as the Glastonbury mineral, which would seem on geological grounds nearly coeval with it.

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[105] Radioactive transformations, p. 189.

[106] U. S. Geological Survey, Monograph 29, 1898.

[107] Connecticut Geological and Natural History Survey, Bulletin 6, 1906, p. 116.

[108] American Journal of Science, vol. 23, 1907, p. 87.

[109] American Journal of Science, vol. 28, 1884, p. 431.

[110] Hidden & Mackintosh: American Journal of Science, vol. 38, 1889, p. 474. Hillebrand: American Journal of Science, vol. 46, 1893, p. 99; vol. 13, 1902, p. 145.

"I find no convincing evidence that the law of decay is so simple as is assumed. Under the conditions in which uranium compounds are stable, λ must necessarily reduce to zero. It is in the highest degree probable that λ is a discontinuous function, and it is to the same degree probable that the law of decay fails like Boyle's law, or that λ varies with circumstances, such as may have environed a mineral in a pegmatite, even though heat alone or pressure alone may be without effect upon radioactivity.

"It does not seem to me that geologists can possibly accept the ages of minerals as determined from the uranium-helium or the uranium-lead ratios, which do not seem consistent and are far longer than stratigraphers could admit." [111]

GEOLOGICAL EVIDENCES OF AGE OF URANIUM MINERALS

Upper Paleozoic age of Glastonbury uraninites.—In reviewing Becker's statements the relative ages of the uranium minerals from the Glastonbury and Barringer Hill localities should be given first attention. It will be seen that the age ascribed to each is quite clearly in error and that their relative ages are very different.

In regard to the location and age of the Glastonbury uranium minerals, Hillebrand in 1890 ascribes them to Hale's quarry, but Becker overlooks the statement which Boltwood makes in the article which forms the basis of Becker's discussion. Boltwood states:

"I have been informed by Mr. E. B. Hurlburt, of Glastonbury, Connecticut, who has made a careful study of the mineral occurrences in his locality, that he considers it to be highly improbable that the specimens examined by Hillebrand and described as from Glastonbury were actually found in that place, or even in the neighboring quarries of South Glastonbury. Columbite, monazite, a mineral resembling polycrase, and autunite are found at South Glastonbury; but Mr. Hurlburt, who has looked into the matter quite thoroughly, is of the opinion that the specimens of uraninite credited to Glastonbury must have been found in the feldspar quarries of Portland, a town on the east bank of the Connecticut River between South Glastonbury and Middletown. A number of years ago uraninite in some quantity was found at Portland, and as some of the workmen in the Portland quarries had their homes in South Glastonbury, its occurrence in the latter locality may readily have been assumed by the collectors who afterward obtained the specimens. It is also equally possible that the specimens in many collections labeled as from Middletown are also really from Portland." [112]

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[111] Relations of activity to cosmogony and geology, loc. cit., 1908, pp. 133-135.

[112] B. B. Boltwood: On the ultimate disintegration products of the radioactive elements. Part II.—The disintegration products of uranium. Am. Jour. Sci., vol. xxiii, 1907, pp. 77-88; see p. 81.

Now these feldspar dikes of Portland are intruded into the Bolton schist, and so also are nearly all of those in the town of Glastonbury.[113] All the feldspar deposits and their uranium minerals come from pegmatites. As no fossils have been found in the metamorphic rocks of Connecticut, the age relations are in many places obscure. Nevertheless Rice and Gregory consider that the relations to the rocks of eastern Massachusetts suggest a late Paleozoic age for most of the schists east of the Connecticut River, though they do not exclude the possibility of an earlier Paleozoic age. These authors do not express any opinion as to the age of the Glastonbury gneiss, but state that it is "of uncertain origin."[114] There is no evidence, however, that it is Cambrian. The placing of the Wilbraham gneiss, the Massachusetts equivalent of it, in the Cambrian goes back to a decade when the banded or mashed granite-gneisses were generally believed by the students of New England geology to be of sedimentary origin. Part of them were regarded as Archean, another part as basal Cambrian. As Van Hise explains, the placing of a great series of granite-gneisses in the basal Cambrian was a natural error, owing to the intricacy of the structure and the fact that the Cambrian has at its base an arkose formation which in places is quite similar in appearance to the granulated granites from which they were in part derived.[115] Before 1908, however, Emerson had recognized that much of what was formerly regarded as sedimentary gneiss of Cambrian age in western Massachusetts was in reality an Archean basement of igneous origin. In 1898 Emerson placed the Belchertown tonalite and Williamsburg granite, covering large areas near the Connecticut Valley, in the Carboniferous.[116] The map showing these formations did not include, however, the eastern upland. In 1916, in a preliminary geologic map of Massachusetts and Rhode Island,[117] Emerson assigns a late Carboniferous or post-Carboniferous age to the Monson granodiorite, which is the Massachusetts extension of the Connecticut Glastonbury gneiss. Thus there has not been at any time a sufficient basis for assigning a Cambrian age to the Glastonbury or Portland uraninites. The evidence of the late or post-Carboniferous age of these granites is derived from a region farther east in Massachusetts, where granites cut schists in which Carboniferous plant fossils have been found. It appears to the writer that all which can at present be positively stated in regard to the Glastonbury uraninites is that they are upper Paleozoic. Granitic intrusions occurred repeatedly in New England and appear to have covered quite a range in time, since Carboniferous formations rest in places upon somewhat older granites as well as being cut by those of younger age.

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[113] E. S. Bastin: Economic geology of the feldspar deposits of the United States. Bull. 420, pl. vi, U. S. Geol. Survey, 1910.

[114] ——— Rice and H. E. Gregory: Manual of the Geology of Connecticut, p. 114, Bull. No. 6, Conn. Geol. and Nat. Hist. Survey, 1906.

[115] C. R. Van Hise and C. K. Leith: Precambrian geology of North America. Bull. 360, U. S. Geol. Survey, 1909, pp. 587-592.

[116] B. K. Emerson: Holyoke folio, U. S. Geol. Survey, 1898,

[117] U. S. Geol. Survey. To be published in 1917.

Middle Precambrian age of the Llano series.—As to the age of the pegmatites in the Llano series in Texas, Becker bases his statement that they are "not far below the Cambrian" on a brief observation by Walcott, made 24 years previously, on what the latter guardedly calls a "hurried reconnaissance of a portion of the Paleozoic area of Central Texas, the chief object in view being the study of the Cambrian section and the collecting of fossils from the Texas Potsdam horizon."[118] The rocks which lay unconformably below the Upper Cambrian (Potsdam) Walcott named the Llano group and correlated them with the Grand Canyon group, which at that early time he placed in the Paleozoic, but later removed to the Precambrian. Walcott notes that on Roessler's map of Llano County (1875) all of the Llano group is referred to as "granitic, metamorphic, and igneous" and has been considered as Archean. He, however, states that he did not observe any rocks of undoubted Archean age.

In the Llano-Burnet folio, Texas,[119] this region is mapped and its geology discussed in detail. Paige gives the following in regard to the character and age of the Llano series:[120]

> "The Llano series has proved to be a completely metamorphosed series of schists, marbles, and gneisses and can be classified as Algonkian in contradistinction to Archean only on the very broadest evidence, such as the preponderance of metamorphic sediments over igneous material. Roessler's description of these rocks as granitic, metamorphic, and igneous was therefore concise and, possibly except for his reference of the series to the Archean, correct."

The granites intrude the Llano series in great volume and the uranium minerals are in pegmatites related to the granites. Thus the age is distinctly Precambrian. The geological relations do not prove more, but the general character is similar to the intrusive granites of the middle Precambrian of Canada, the Huronian or post-Huronian of some authors, the late Archean as defined by Lawson. These are the Lorrain, or Algoman granites, as they have been variously named. Thus there is no such closeness of age as Becker concluded to exist between the Glastonbury (Portland) uraninites and the radioactive minerals of the Llano series.

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[118] C. D. Walcott: Note on Paleozoic rocks of central Texas. Am. Jour. Sci., vol. xxiii, 1884, pp. 431-433.

[119] Sidney Paige: Geologic atlas of the United States, No. 183, U. S. Geol. Survey, 1912.

[120] Loc. cit., p. 2.

THE LEAD-URANIUM RATIOS OF THE LLANO MINERALS

The original analytical data.—The lead-uranium ratios should be widely different for the Connecticut and Texas regions, but they should be accordant among themselves. Such accordance exists among the Glastonbury analyses, though the force of the accordance is perhaps somewhat weakened by the determinations being all from one species of mineral, uraninite. For the Llano region a variety of analyses and from different mineral species are available, but in the published lists no constancy is shown in the lead-uranium ratio. Becker from the varying ratio obtains ages as cited, ranging from 1,671 million years to 11,470 millions, and takes the variation, the maximum being about seven times the minimum, as evidence of the unreliability of the method for measuring age. Holmes gives a list of values of the lead-uranium ratio ranging from 0.102 to 1.130. He ascribes the variations in ratio to the altered character of the minerals, riddled with secondary products, and speaks of them as eloquent of the uselessness of this series of minerals as an index of geological time.

URANIUM MINERALS OF THE LLANO DISTRICT, TEXAS

Analyses giving Lead-Uranium Ratios

Used by Boltwood (1907)

Arranged in order of increasing ratio; minor constituents omitted

	No. 15. Uraninite. Mackintosh.	No. 14. Uraninite. Hillebrand	No. 16. Mackintoshite. Hillebrand.	No. 17. Yttrocrasite. C. H. Warren.
UO_3	46.75	44.17	.....	0.64
UO_2	19.89	20.89	22.40	1.98
ThO_2	7.57	6.69	45.30	8.75
ZrO_2	.....	0.34	.88	.....
Rare earths.........	11.22	12.16	1.86	28.59
PbO	10.16	10.08	3.74	0.48
Fe_2O_3	0.58	.....	.....	1.44
FeO	.....	.....	1.15	.....
SiO_2	.....	.....	13.90	.....
TiO_2	.....	.....	.....	49.72
H_2O	2.54	1.48	4.31	4.36
Total........	99.93	98.74	96.50	100.57
Ref.: Am. Jour. Sci., volume and page..	38.481.	42.391.	46.101.	22.516.
Year	1889	1891	1893	1906
Pb	9.43	9.35	3.47	0.45
U	56.45	55.18	19.75	2.28
Pb/U	.167	.170	.176	.195

URANIUM MINERALS OF THE LLANO DISTRICT, TEXAS

Analyses giving Lead-Uranium Ratios

Used by Becker (1908)

Arranged in order of increasing ratio; minor constituents omitted

	A. Nivenite. (Uraninite). Mackintosh.	B. Mackintoshite. Hillebrand.	C. Fergusonite. (Trihydrated). Mackintosh.	D. Yttrialite. Hillebrand.	E. Fergusonite. (Monohydrated). Mackintosh.	F. Yttrialite. Mackintosh.
UO_3	46.75	.....	3.12	.....	1.54	0.83
UO_2	19.89	22.40	3.93	1.64	.....	.....
ThO_2	7.57	45.30	0.83	10.85	3.38	12.00
ZrO_2	.....	.88	.....	.....	.....	.....
Rare earths......	11.22	1.86	31.36	51.70	42.33	51.30
PbO	10.16	3.74	1.94	.80	1.43	0.854
Fe_2O_3	0.58	.....	3.75	.76	0.98	.....
FeO	.....	1.15	.....	1.96	.....	2.89
SiO_2	.....	13.90	.....	29.63	.....	29.17
TiO_2	.....	.....	.....	.05	.....	.....
Cb_2O_5	.....	.....	42.79	.....	46.27	.....
H_2O	2.54	4.31	7.57	.32	1.98	0.79
Total......	.....	.....	99.80	100.00	98.95	99.754
Ref.: Am. Jour. Sci., volume and page	38.481.	46.101.	38.484.	13.149.	38.483.	38.478.
Year	1889	1893	1889	1902	1889	1889
Pb	9.43	3.47	1.80	0.74	1.33	0.79
U	56.45	19.75	6.06	1.45	1.28	0.69
Pb/U	.167	.176[121]	.297	.513	1.035	1.147

A is the same as No. 15; B is the same as No. 16.

A careful review of the original analyses, however, brings to light unexpected errors and by their elimination results in a good degree of accordance among those minerals whose compositions give indications of a reliable lead-uranium ratio. To demonstrate this statement the following tabulation is given, the percentages of lead and uranium and the value of their ratio being the result of recalculations by the writer from the original publications of the analyses. It is clearly impossible to give proper weight to the value of the ratio unless the percentage occurrences of uranium, lead, thorium, and a number of other constituents are noted. These are assembled and published for this purpose for the first time.

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[121] Given by Becker as .3894, apparently as the result of an arithmetical error.

Discussion of the value of the analyses.—In comment upon these analyses it should be noted that nivenite of Becker's list is the same analysis as number 15, uraninite, of Boltwood's list.

Number 14 is a different lot of the same material as number 15. The remarks of Hillebrand, therefore, apply to both. Hillebrand states that "a first glance sufficed to show that the specimens were not fresh, and therefore analysis could throw no light on the ultimate composition of the mineral. The cause of the considerable loss shown by the total of 98.74 for the analysis is not known." Notwithstanding Hillebrand's comments on the lack of freshness, it would appear that these analyses are of fair reliability—that is, that no appreciable amount of either lead or uranium has been removed by solution in meteoric waters, since the amount of combined water is not abnormal for a uraninite and the large amount of uranous oxide shows an absence of oxidizing weathering.

Number 16, mackintoshite, shows from the presence of uranous and ferrous oxides in large amount and the complete absence of uranic and ferric oxides a lack of oxidation by descending waters. The material was embedded in massive cyrtolite and associated with fergusonite. It is opaque and black, and alters on the surface to dull yellowish brown thorogummite, a hydrated and oxidized uranium thoro-silicate holding 7.88 per cent of combined water. An analysis is given of thorogummite showing that the change is almost entirely one of oxidation and hydration. In comment Hillebrand states:

> "It is in fact remarkable, considering the great molecular alteration that must have taken place, as determined by the totally different appearance of the two minerals, that so little loss of substance has taken place. Almost the sole change has consisted in an oxidation of uranous oxide and an increase in the hydration. These facts render not altogether safe the assumption above made that all uranium and iron in the new mineral exist there in the lower forms of oxidation, and they furthermore indicate that the black mineral itself may have already undergone oxidation and hydration without this being manifest to the eye—a supposition which is strengthened by the loss at 100° C. of half a per cent of water, and in fact by the intimate union which existed between the two minerals when received. Such material alteration without corresponding physical evidence of it seems to be common among uraninites." [122]

Notwithstanding this possibility of some oxidation and hydration, the smallness of the losses in uranium and lead in the transformation of mackintoshite into thorogummite indicates that no appreciable change in the lead-uranium ratio has taken place in the mackintoshite, the parent mineral. In fact, it is a rather general condition, as Merrill has shown, for the chemical changes due to solution in weathering to be only incipient until hydration and mechanical disintegration have become extensive.[123]

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[122] Am. Jour. Sci., vol. 46, 1893, p. 101.

This mineral appears consequently to be well adapted for determining the age of the formation, but in the analysis it is noted that the total is but 96.50 per cent, indicating a loss of 3.5 per cent. This resulted from the limited quantity of the sample and the presence of the rare earths which required it to be divided into three portions. Hillebrand states that "it is probable that the loss should be distributed somewhat unevenly over a number of the constituents, silica and lead excepted, they being without doubt nearly correct." If 1 per cent of this loss should be added to the 19.75 per cent of uranium, the mineral would possess 20.75 per cent uranium and the lead-uranium ratio becomes .167, exactly the same as for analysis number 15, in which the total amounts to 99.93.

In regard to number 17, yttrocrasite, Hidden and Warren make the following observations:

> "The crystal from which the material for analysis was selected was found in Burnet County, Texas, by Mr. John J. Barringer, who discovered the famous gadolinite mine just across the Colorado River, in Llano County, now known as Barringer Hill.
>
> "The crystal had a thin dull brown coating of amorphous material which was evidently an hydrated alteration product, very similar to the yellowish brown coating observed on the polycrase (?) of North and South Carolina. The fresh underlying material is black in appearance and has a bright, pitchy to resinous luster, and closely resembles that of polycrase and euxenite, and like these has an uneven and small conchoidal fracture. Its hardness is between 5.5 and 6.
>
> "The mineral when examined between crossed nicols is seen to consist of a mixture of isotropic and a feebly double refracting material. In several instances a distinctly spherulitic structure was observed with high powers; otherwise nothing of a definite nature could be made out regarding the optically active portion. The mineral is not now, therefore, of a strictly homogeneous structure. The fact, taken into consideration with its content of water and carbon dioxide, 0.68 per cent, suggests that the mineral is a hydrated alteration of an originally anhydrous species. It may be mentioned here that a very similar heterogeneous structure has been also noticed as characteristic of specimens of polycrase (?) from North and South Carolina."[124]

In this connection should be discussed the significance of the hydration. If it is due to the leaching of descending ground waters it would indicate a geologically recent alteration, which would raise doubt as to the value of the lead-uranium ratio. The rather well crystallized nature of certain of the uranium and thorium hydrates and the lack of accompanying oxidation suggest, however, that the hydration was accomplished in a decadent stage of the pegmatitic crystallization. Such deep-seated hydration by *ascending* hydrothermal waters tends to be pervasive, owing to the high internal pressures and temperatures of the solutions, favoring diffusion. Hydration due to the *descending* waters connected with weathering is, on the contrary, characteristically not pervasive until admission to all parts of a rock is prepared by an intimate crackling. Now a hydration dating back to a decadent stage of the pegmatization might change the content of uranium at that time, but would not affect the present lead-uranium ratio. In view of these and other considerations, it would appear that Holmes has been misled in speaking of the altered character of these minerals as eloquent of their uselessness as an index of geological time. The material on the market has all come from shallow pits, weathering has altered the surface, but this recent action is distinct from what appear to be primordial alterations. Furthermore, these occurrences fortunately are within the inner valley of the Colorado River, just above the flood-plain level, are 500 feet below the old upland of the surrounding country, and have consequently been exposed to erosion during only the last cycle of valley-cutting. It is found in general that, in rock outcrops exposed only to this last cycle of erosion, comparatively little chemical alteration of the bedrock has been accomplished by weathering. Under the higher uplands ground water has been active for very much longer periods of time, but in the bottoms of the inner valleys, on the contrary, the rocks are much fresher closer to the surface, indicating that the valley erosion has been more by mechanical breakage accompanied by superficial alteration.

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[123] G. P. Merrill: Rocks, rock weathering, and soils.

[124] Am. Jour. Sci., vol. 22, 1906, p. 515.

Although in this yttrocrasite the uranium is small in amount, yet so far as the analytical errors are concerned the analysis is of a high order. Boltwood states:

> "The writer (Boltwood) had the good fortune to meet Professor Warren at the time this analysis was in progress and the latter kindly consented to take especial precautions in the determination of the lead and uranium." [125]

Experience seems to show, according to Holmes, that thorium minerals give unreliable indices of age because some original lead is apt to be found in such minerals with the lead originating from uranium. The degree of admixture of original lead doubtless varies with the region and also the mineral. Its quantity may be estimated by a careful determination of the atomic weights, since the original lead appears to be mostly not derived from the uranium series. The uraninite of the Llano region is sufficiently abundant, so that this test should be applied. The analyses which have been given, however, carry internal evidence that in the Llano region such original lead must be very small in quantity. In the minerals where the percentage of uranium lead is small and thorium is large the original lead should notably modify the lead-uranium ratio. Now, in analysis number 17, U is only 2.28 per cent, Pb is 0.45, and ThO_2 is 8.75. The Pb/U ratio is nevertheless only .195, which is but one-sixth greater than the most probable value. The presence of .08 per cent of original lead would account for this increase in the ratio, which is but one-one-hundredth of the ThO_2 present. On the other hand, analytical errors which come in with the determination of small quantities may be more important than original lead. Furthermore, the agreement of the ratio, as derived from four analyses and three different minerals which show great ranges in the amounts of uranium and thorium, is another indication of the reliability of the ratio and the smallness of the amount of original lead.

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[125] Am. Jour. Sci., vol. 23, 1907, p. 82.

On assigning weights to the several determinations, the greater weight should be given to the minerals high in uranium, since this decreases the errors due to original lead and to analysis. Some slight and variable amount of original lead may be granted in all of these minerals. Therefore the best value of the ratio for the Llano region may be taken as .165. This corresponds to an age of 1,125,000,000 years.

Explanation of previous discordant results.—Having reached this conclusion as to the value of the ratio in the uraninite of the Llano region, attention must be turned to an explanation of the entirely different conclusion reached by Becker and quoted on a previous page. In the six analyses used by Becker no two give similar ratios and these range in value from .167 to 1.147. As Becker does not state that Boltwood had used four analyses giving accordant ratios from this region, the reader, unless intimately familiar with Boltwood's article, would assume that no analyses from the Llano County minerals give accordant results. How different this is from the facts has been shown on the previous pages. Becker, for some unknown reason, avoided using two ratios of Boltwood's list and apparently made an arithmetical blunder in recomputing the lead-uranium ratio from a third. Instead of getting .18, as Boltwood did, or .176, as computed by the writer to another significant figure, Becker derives a ratio of .3894. Thus, if Becker had included correctly all of Boltwood's list, there would have been four highly accordant ratios in a total of eight—a very different result from no two similar ratios among six analyses.

Let attention be given next to the four analyses used by Becker which Boltwood did not use. On page 864 the six analyses which are the basis of Becker's conclusions are listed, not in the order given by Becker, but in the order of decreasing uranium content. It appears also that this is the order of the *increase* in the lead-uranium ratio. As the uranium in the four additional analyses is but 6.06 per cent in the first and ranges in the remaining three from 1.45 down to the small quantity of 0.79 per cent, the relations clearly indicate the worthlessness of these analyses as tests, compared to minerals as high in uranium as are uraninite and mackintoshite; yet, as Becker does not give in his article the per cents of lead and uranium, but only their ratio, this conclusion could not be suspected from his paper. The thorium in the last three analyses greatly exceeds the content of uranium. Some original lead is suggested by the regular increase of ratio with decrease in uranium. The amount of original lead implied, provided the analytical work is very accurate, would be from approximately 0.5 to 1.0 per cent. Small errors in the analyses would, however, greatly change the ratios between quantities so small, and seems to the writer to be probably the more important factor. The small changes which are likely to have resulted from the incipient alteration so common in these minerals would also greatly affect the results. That we may have to look to analytical errors and incipient alterations more than to original lead for the explanation is suggested by the fact that gadolinite, a silicate of the rare earths from the same region, shows in its analysis by Mackintosh neither uranium nor lead. No thorium is present either, but Ce_2O_3 occurs to the extent of 2.66 per cent. As cerium is very similar to thorium in its chemical properties, original lead might be expected to accompany it if it accompanies thorium. The same is true of rowlandite.[126]. Hess gives a complete list of the minerals found at this locality.[127] Although chalcopyrite, pyrite, spalerite, and molybderite are listed, galena does not appear. It appears, then, that original lead must have been very rare in the solutions which gave rise to these minerals.

From this examination of the evidence it is seen that the four analyses rejected by Boltwood but used by Becker are, as Boltwood stated, not suitable for throwing any definite light on the lead-uranium ratio for Llano County.

Attention must next be given to the explanation of the discordant ratios for the same region reached by Holmes, whose list is as follows:[128]

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[126] Bull. 419, U. S. Geol. Survey, 1910, p. 276.

[127] F. L. Hess: Minerals of the rare-earth metals at Barringer Hill, Llano County, Texas. Bull. 340 D, U. S. Geol. Survey, 1908, pp. 63-65.

[128] A. Holmes: Radioactivity and the measurement of geological time. Proc. Geologists Asso., vol. xxvi, part 5, 1915, p. 303.

Table D

Radioactive Minerals from Llano County, Texas, United States of America[129]

Analyst.	Mineral.	Lead.	Uranium	Pb/Ur.
1. Mackintosh........	Yttrialite	0.8	0.71	1.13
2. Mackintosh........	Yttrialite	0.8	0.75	1.07
3. Mackintosh........	Fergusonite	1.3	1.28	1.01
4. Hillebrand.........	Yttrialite	0.76	1.5	0.51
5. Mackintosh........	Fergusonite	1.8	6.14	0.29
6. Hillebrand.........	Mackintoshite	3.65	19.6	0.186
7. Mackintosh........	Cleveite	10.25	55.2	0.186
8. Hillebrand.........	Mackintoshite	3.47	19.7	0.176
9. Hillebrand.........	Uraninite	9.4	55.0	0.170
10. Mackintosh........	Nivenite	9.45	56.1	0.168
11. Mackintosh........	Bröggerite	7.82	67.2	0.116
12. Mackintosh........	Thorogummite	2.01	19.7	0.102

Number 1 appears to be F of Becker's list.

Number 2 the writer has not been able to identify.

Number 3 is E of Becker's list.

Number 4 is D of Becker's list.

Number 5 is C of Becker's list.

Number 6 appears to be from an incomplete analysis by Hillebrand: American Journal of Science, volume 46, page 101, analysis *b*. The thorium and rare earths were lost, and Hillebrand states that the percentage of UO_2 would be slightly increased by uranium which was not separated from the earths. The analysis therefore has no value as compared with number 8.

Number 7 is not from Llano County, but apparently from Norway. It is given on page 482, American Journal of Science, volume 38, 1889, for purposes of comparison with nivenite. The analyst was Lindström, as given in Dana's System of Mineralogy, edition of 1911, pages 890, 891. The responsibility for the error rests in greater part on Mackintosh, as it is only by reading the text that one discovers that this is not the analysis of a local mineral. Dana also was misled and incorrectly lists it as coming from Texas.

Number 8 is B, Becker's list, and number 16 of Boltwood's list.

Number 9 is number 14 of Boltwood's list.

Number 10 is A, Becker's list, and number 15 of Boltwood's list.

Number 11 is another Norwegian mineral given by Mackintosh for comparison with nivenite. The analyst was Blomstrand. The same errors have been made as in number 7.

Number 12, thorogummite, occurs as a yellowish brown alteration product of mackintoshite. It is thoroughly oxidized and hydrated. It seems to be a product of recent oxidizing waters, and although it retains a chemical resemblance to the original mineral it has lost over 1 per cent of its lead. According to the calculations of the writer, the uranium is 18.76 per cent, not 19.7, as Holmes has it. This is due to the lesser proportion of uranium in the higher oxide. The uranium has therefore also decreased about 1 per cent, but an equal elimination of both lead and uranium will make a large difference in the ratio. From the nature of the mineral, apart from the chemical analysis, it is clearly unsuited for the present purpose.

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[129] Am. Jour. Sci., vol. xxviii, 1884, pp. 431-433; vol. xxxviii, 1889, p. 480; vol. xlvi, 1893, p. 98.

Eliminating nine of the twelve analyses from Holmes' list for reasons given above, leaves numbers 14, 15, 16 of Boltwood's list and gives for this remainder a highly accordant ratio. These appear to serve, therefore, as a reliable means of measuring the age of the Llano series and add their weight to the value of the method.

PART VI.—CONVERGENCE OF EVIDENCE ON GEOLOGIC TIME AND ITS BEARINGS

METHODS OF TESTING THE AGES GIVEN BY RADIOACTIVITY

In the last third of the nineteenth century physics, in the embodiment of its leaders, Kelvin, Helmholtz, Tait, and others, spoke with assurance on the limits of geologic time. Geologists sought to meet their demands, in so far as they could, but such men as Huxley, Geikie, Goodchild, and others, giving greater weight to the geologic evidence, refused to accept the restrictions which were set. We have lived to see unsuspected sources of energy discovered, stupendous in amount, which wholly remove the former limitations on the age of the earth and set new boundaries far beyond what, to most geologists, has seemed the testimony of the evidence.

After the one experience in the fallibility of physical argument notwithstanding its mathematical character, it would certainly be unwise for geologists to accept unreservedly the new and larger measurements of time given by radioactivity. There may be here, also, factors undetected and unsuspected which vitiate the results. The radioactive measurements, however, can and should be tested by the degree of concordance or discordance of the several results when compared with each other, and also with independent lines of evidence, especially geological.

In the preceding parts of this paper a reexamination has been made of these various lines of evidence. This concluding part will bring these results together and point out what seem promising fields for future investigation. The first conclusion of importance is the essential lack of uniform rate of erosion and sedimentation through geologic time. The introduction of the idea of rhythm as ever-present in geological processes in here made fundamental. It is seen on applying this to the present condition of the earth, as compared to past geologic time, that there exists at present a very unusual rate of aggregate erosion. Joly, overlooking the significance of composite rhythms, holding to the essential uniformity of gelogic processes, and, furthermore, regarding the present rates as representative of all time, concluded that it was impossible to accept the results based on the hypothesis of the uniformity of radioactive disintegration. He pointed out that this would imply that the present rate of supply of sodium to the sea was from ten to fourteen times the mean rate throughout past time. This seemed to him so impossible that to his mind it was easier to think of some unknown factor modifying the rate of atomic disintegration and resulting in a marked slowing of atomic decay with increasing age of the uranium mineral. It has been shown, however, on geologic grounds that there is good evidence for holding that the present rate of denudation is ten or fifteen times the mean rate which has existed since the opening of the Paleozoic. There is thus brought about a general accordance between independent lines of evidence.

There is seen to be even less justification for Becker's assumption that the contribution of sodium from igneous rocks to the sea has been regularly decreasing with the passage of time. So far as the stratigraphic evidence goes, it may or may not have had a higher mean rate in the Precambrian. Areas of Archean rock were then, it is true, more widely exposed, but the repeated baseleveling implies long periods when the lands had been worn low and erosion was very sluggish. Through much of the Paleozoic and Mesozoic, however, the evidence is clear that the continents were widely covered with seas or their deposits, and that the relatively small areas which supplied the waste were generally of low relief. This paleogeographic interpretation is distinctly against the postulate of a regular decrease of new sodium through geologic time, especially a decrease following a logarithmic curve.

The question of the uniformity of rate of atomic disintegration, which is the basis of all calculations on the age of radioactive minerals, has been discussed and, although in the nature of things, a uniformity of disintegration of uranium through geological time can not be directly demonstrated, the evidence from the measured rates of decay of its products points strongly to a similar uniform rate for the parent element. Nothing is known to support a hypothesis that there is an increase in stability of unstable atoms by a process of aging. The temperature and pressure limits, through which the uranium minerals have existed since their formation, are not greater than those within which its more unstable products have been studied in the laboratory. The effects of the profound temperatures and pressures of the earth's interior are, as yet, wholly unknown, but the conditions which exist within the outer crust have been duplicated by experiment.

But may not these moderate ranges affect the rate of disintegration of the more stable parent? That can be tested by geological evidence. If uranium minerals well adapted for age determination and of a well determined stratigraphic position, such as the Devonian, are found in different regions to give notably different ages, it may be an indication of inhibition of disintegration beyond certain limits of temperature and pressure which have existed in these formations through a part of their existence. Unfortunately the data are as yet too meager for this test to be so precisely applied. Most of the uranium minerals come from formations whose stratigraphic positions are not closely known, and they represent a wide range of geologic occurrence. There is another test, however, which can be reasonably well applied. That is the test of proper sequence. If the rate of disintegration of uranium is altered by physical conditions within a few miles of the surface, then, in a considerable number of instances, some range in the lead-uranium ratio might be expected within the minerals of a single district; but the more searching test is found when the measurements of the age of minerals of widely different regions and stratigraphic positions are assembled according to sequence of age as determined by the radioactive transformations. It would be expected that, if variable rates of disintegration prevailed, the geologically younger mineral would in some instances show a greater amount of disintegration products and indicate an apparently greater age. With a wide range in age, with many points determined, and a large list of minerals, this argument begins to assume great force, notwithstanding considerable indefiniteness in the geological evidence regarding the exact stratigraphic position of many of the minerals.

This test could be, and was, applied to the first paper on the subject, published by Boltwood in 1907. It showed that his work bore internal evidence of the essential correctness and importance of the hypothesis of the lead-uranium ratio as a means of determining age, though a number of subordinate and modifying questions remained to be settled, especially in regard to the presence of various kinds of lead. This internal evidence was stated by Boltwood, in 1907, as follows:

> "The actual value of the ratio varies considerably for the primary minerals from different localities, the maximum value being about six times the minimum. It is beyond the writer's province to discuss the data bearing on the geological ages of the different deposits; but he is indebted to Professor Joseph Barrell, of Yale University, for the statement that, so far as the knowledge of the latter extends, the relative values of the ratios are not contradictory to the order of the ages attributed by geologists to the formations in which the different minerals occur.
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> "From the data which have been presented in the preceding tables, it is apparent that the requirements for a disintegration product of uranium are fulfilled by lead within the limits of probably experimental error. On the basis

of this evidence the assumption would appear to be justified that lead is the final product of uranium."[130]

As has been noted, Becker argued that the sequence of geological age was in certain examples directly opposed to Boltwood's conclusions, but in a preceding section it has been shown that Becker's conclusions were based on a series of errors.

With an increasing recognition of the importance of the radioactive methods, it is to be hoped that the problem will be directly attacked, and from the standpoint of geologic science, rather than left almost wholly as incidental investigations of the radio-chemist. Minerals high in uranium are, however, rare. Those with only accessory uranium are seen to be relatively unreliable because of the small amount of uranium, the still smaller amount of uranium lead, and the large changes in the ratio which may result from analytical errors, original lead, temporary thorium lead, or other causes.

It would seem, however, that the ratio of helium to uranium and thorium might be made of high supplemental value in a manner which, so far as the writer is aware, has not been used. Holmes has pointed out that the helium content of uranium and thorium minerals is always less than the amount of helium which has been generated, because of the leakage of the gas. Nevertheless, in fresh rocks which contain such minerals, no matter what their age may be, there is reason to believe that the helium is mostly present, though in part outside of the parent mineral. It is known that fresh unbroken rock is practically impermeable, as is shown by the storage of carbon dioxide under high pressure in microscopic vesicles. The very freshness of the rock proves, furthermore, the lack of permeation of surface waters. The helium generated in the small minerals, such as zircon, will be in part ejected by the initial velocity of the atom; in part it will slowly diffuse into the adjacent minerals, owing to the accumulating excess of vapor pressure within the mineral. In an uncleaved rock it will, however, practically all remain within a very limited distance. In those parts of a rock-mass where uranium and thorium are concentrated in appreciable quantity, the amount of new helium would be large in comparison with original helium. In a rock containing zircon, biotite, minerals of the rare earths, or other minerals holding uranium or thorium, if a cube several centimeters in diameter were cut from the fresh rock and the whole subjected to analysis, the amounts of uranium, thorium, helium, and lead might be ascertained by virtue of the large volume of material, and the quantity of helium should approach more nearly the theoretic amount.

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[130] B. B. Boltwood: On the ultimate disintegration products of the radioactive elements. Part II.—The disintegration products of uranium. Am. Jour. Sci., vol. xxiii, 1907, pp. 83, 84.

AGE POINTS GIVEN BY URANIUM MINERALS

By diligent search the evidence of age based on uranium minerals can, without doubt, be greatly increased. With that which is at present available it is desirable, however, to construct a tentative table of geologic time.

In regard to the table of ages given on page 846 by the helium ratio and quoted from Holmes after Strutt, it should be noted that certain of the ages are open to question. In the Eifel, New Zealand, and Auvergne occurrences the zircons may have been derived from older rocks.[131] The Pliocene age of the Campbell Island, New Zealand, formation is, furthermore, open to question. The hematite from County Antrim, Ireland, offers a maximum age, 30,800,000 years, for a Tertiary occurrence of a helium mineral, and, furthermore, occurs associated with leaf beds which serve to fix the age within comparatively narrow limits. Heer originally classified these beds as Miocene. With the separation of the lower Miocene as Oligocene they become Oligocene. Gardner, however, maintained later that they were lower Eocene. In order to obtain the latest opinion the writer submitted the question of their age to Professor E. W. Berry, who kindly replied as follows:

> "Regarding the age of the Antrim basalts with the intercalated leaf beds—Heer's Miocene was of course 'old Miocene'—that is, Oligocene. I am quite sure that their age is not Lower Eocene, as J. Stanley Gardner held, and it is my opinion that they are either Upper Eocene or Lower Oligocene, and by that I mean either Bartonien (as restricted to the Upper Bartonien after segregating the Auversien below) or Sannoisien (Lattorfien). It is increasingly difficult to paleobotanically differentiate the *temperate floras* of late Eocene and early Oligocene times, although it is easy enough in lower latitudes, as, for example, in southern Europe or southeastern North America.
>
> "I think the evidence is rather good for considering all of the far northern basaltic sheets associated with the plant beds of the 'Arctic Miocene flora' (Mull, Iceland, West Greenland, etcetera) as essentially synchronous and as contemporaneous with the most tropical floras and marine faunas of lower latitudes, as, for example, those of the Jackson and Vicksburg of our Southern States. Correlation by old-fashioned methods is not possible for a variety of reasons, chiefly since Heer, who was the original describer of most of the Arctic floras, brought to that study a profound acquaintance with the Miocene floras of central Europe, and in subsequently dealing with these more fragmentary northern floras he often saw resemblances that did not exist. Both

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[131] R. J. Strutt: The accumulation of helium in geological time. III. Proc. Royal Soc. London, vol. 83, ser, A, 1910, p. 301.

in America and in Europe we commence to get a northward spread of plants from the equatorial regions in the Lower Eocene (for example, in the Wilcox). This is emphasized in the Middle Eocene (Claiborne and the corresponding Upper Lutetien and Auversien) and culminates in the Upper Eocene and Lower Oligocene. Several of the Lower and Middle Eocene types of our Gulf States appear in the flora of west Greenland and in the Kenai flora of Alaska, etcetera, and, granting the time necessary for dispersal and considering the forested condition of the country north to latitude 75°, it seems to me that this should make these northern floras correspond to the time when the most tropical floras and faunas flourished farther south."

Let it be assumed that the beds are Lower Oligocene and that but little helium has been lost, or that they are Upper Eocene and somewhat more helium has been lost. The length of the whole of Cenozoic time may then be regarded as 50 per cent longer, giving 55,000,000 to 65,000,000 years. This is obtained by considering from stratigraphic evidence that the Eocene constitutes at least one-third of the Tertiary period. The mean figure of 60,000,000 years is twenty times as long as the conventional estimate of 3,000,000 years, but a discussion has been given in a preceding section which goes to show that the geologic evidence demands that this figure of 3,000,000 should be increased to the order of magnitude set by the helium measurement. The two independent lines of investigation and the nature of the helium measurement are in sufficient accord to warrant accepting the round figure of 60,000,000 years as a provisional estimate for the length of Cenozoic time.

We come next to a group of Upper Paleozoic occurrences in which the precise geologic position, or the possible presence of some original lead, is in most cases undetermined.

First come the Glastonbury uraninites, previously discussed in this article. Emerson regards the age of the associated igneous rocks as late or post-Carboniferous. They are clearly Upper Paleozoic, but the granitic intrusions in New England and the Maritime Provinces are known to range from the Devonian onward, and some of them may be dated from the Taconic disturbance at the close of the Ordovician. So far as the writer is aware, the schists cut by the Glastonbury pegmatites might possibly be as early as sub-Carboniferous, the Mississippian period of present American nomenclature, but there is no real evidence for Holmes' positive statement that the granite intrudes Lower Carboniferous strata. Caution and latitude are desirable in this regard. The lead content averages about 3 per cent, giving reliable determinations, and the lead-uranium ratio is .041, giving an age of 300,000,000 years. No determinations of the atomic weight of the lead have been made, but the lead-uranium ratio is very constant in the several analyses, suggesting that but little is present. The geological age can not be later than the close of the Permian. Uraninites from the Carolinas gave Richards and Lembert an atomic weight of 206.4. This suggests that some of the lead of those uraninites may be primary, as this is higher than the lowest atomic weights which have been found for uranium lead. The 300,000,000 years for the Connecticut uraninites should therefore be a maximum. In the table as given on a following page for the column of maximum ages it is seen that for any probable correction in age due to original lead the minerals would still fall within the Carboniferous, including Pennsylvanian and Permian. In the column of minimum ages the Glastonbury uraninites fall into the close of the Devonian. Although this does not seem so probable, it is not positively excluded by the evidence. The column of minimum ages is based for the Paleozoic on the Middle Devonian age of the uranium minerals from Brevig, Norway. The two determinations, although in the proper sequence of age, do not agree closely with each other in the amount of time which elapsed between them. Another possibility is that the Glastonbury uraninites are in reality late Carboniferous, with an age of about 200,000,000 years, but with one-third of the lead original, giving an age about 50 per cent too great. More probably the truth lies in some adjustment between several of these factors. On the whole, the column of minimum ages should for the present be regarded as probably nearer to the truth. Nevertheless, uraninites, from the Carolinas, with an estimated correction for primary lead made by means of the atomic weights, give an age between 310,000,000 and 345,000,000 years. Their geologic age is, however, unknown, further than that they are now regarded as Paleozoic and probably Upper Paleozoic. Their most probable position is Carboniferous, either Pennsylvanian or Permian.

The next older determination is of Devonian minerals from Brevig, Christiania district, Norway. It is seen from the tables previously given, page 853, that the per cent of lead is very small, ranging in twelve determinations from .001 to .037 per cent. The lead-uranium ratio, ranging from .040 to .062 in different minerals, nearly constant to the second decimal place, considering the small amounts of lead, may be taken as evidence of the accuracy of the analytical work by Holmes, and also of the absence of more than a trace of original lead. Holmes and Lawson give an elaborate discussion of this question in a recent paper,[132] showing that thorium-lead is not present. Holmes gives the mean age as 370,000,000 to 380,000,000 years, which should be corrected to 345,000,000 to 355,000,000 years. If, however, the anomalous pyrochlore with Pb/U ratio of .062 is omitted for reasons stated by Holmes[133] and the analyses with less than 0.14 per cent of uranium are rejected because of lessened analytical reliability, a lesser age is obtained. By weighting the remaining six analyses according to the content of uranium a mean lead-uranium ratio of .043 is obtained by the writer, or from the whole list of analyses thus weighted .045. These ratios correspond to ages from 315,000,000 to 330,000,000 years. It would seem safer to take the age as no higher than the latter of these figures.

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[132] Lead and the end product of thorium. Philosophical Mag., 6 ser., vol. 28, 1914, pp. 823-840.

Regarding the geological position, Holmes makes the following statement:

> "In this area there is a nearly complete sequence of early Paleozoic rocks. Above these strata there are a few beds of red sandstone of Lower Devonian age. Over these beds and intercalated with them are lava flows; and, finally, penetrating the whole mass, representing a later phase of this period of igneous activity, are great intrusions of plutonic rocks. Among the earliest of the intrusions is a series of thorite-bearing nepheline syenites. Brögger believes them to be of Middle or Lower Devonian age, most probably the latter. The minerals occurring in them are, in many instances, notably radioactive, and thus they afford an admirable series in which to investigate the consanguinity of lead and uranium. Several of these minerals were obtained from Brevig, and estimations of these elements in each case were made." [134]

Arthur Holmes adds later:

> "A recent discovery of *Osteolepis* proves that the sediments upon which the igneous rocks are intruded belong to the Middle rather than the Lower Devonian, and the age assigned to the nepheline syenites from which our minerals were taken is not far removed from this, being almost certainly Middle Devonian." [135]

It should be said, however, that *Osteolepis* is not clearly Middle *Devonian,* but belongs more precisely to the Middle Old Red or Orcadian deposits. These are probably somewhat older than the marine division of Middle Devonian, the greater break, corresponding to Middle Devonian time, occurring between the Middle and Upper Old Red formations. The minimum table of geologic time, on page 885 of this article, is arranged so that 330,000,000 years falls early in the Middle Devonian; 315,000,000 years falls early in the Upper Devonian. In the column of maximum ages this age of 315,000,000 to 330,000,000 years falls into the first half of the Pennsylvanian, a period of great diastrophism. This shift in age brings to attention a discrepancy in the evidence noted also in the discussion of the Glastonbury, Connecticut, uraninites. The Brevig, Norway, rocks are indicated as only 15,000,000 to 30,000,000 years older than the Glastonbury uraninites; but according to the geological positions which have been assigned to the one by Brögger and to the other by Emerson, all of the Pennsylvanian and Mississippian periods and parts of the Permian and Devonian lie between the two. Taking the ratios of ages of these periods to the whole length of time as given by stratigraphical studies, there should be from 100,000,000 to 150,000,000 years between them. This discrepancy may be reconciled by finding that some original lead is in the Glastonbury uraninites, or the stratigraphic ratios may be seriously in error, or, what is more probable, the geological position of one or both is in considerable error. As has been pointed out, but little is positively known regarding the age of the Glastonbury uraninites, further than that they are Upper Paleozoic. In regard to the geological position of the Brevig, Norway, uranium minerals, they belong to the second series of igneous rocks in a total of six series. The first series is interbedded as extrusives in the Middle Old Red sandstones, and Brögger regards the second series as related and but slightly younger. The actual age of the younger series is, however, not fully proven.[136] It appears, nevertheless, that greater weight should be attached to the Brevig than to the Glastonbury occurrences. The column of minimum ages may be regarded as having greater weight than the column of maximum ages.

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[133] Proc. Royal Soc. London, vol. 85, ser. A, 1911, p. 254.

[134] Proc. Royal Soc. London, vol. 85, ser. A, 1911, p. 251.

[135] Philosophical Mag., 6 ser., vol. 28, 1914, p. 831.

Of course, the question might also be raised here if the discrepancy does not throw doubt on the fundamental assumption of the uniform rate of decay of radioactive substances through geological time. The whole body of evidence is, however, sufficiently in accordance to indicate that this is the more improbable explanation.

The next older series of minerals comes from Branchville, Connecticut, and consists of uraninites giving in four analyses a lead-uranium ratio of .053 to .054,[137] the mean corresponding to an age of 390,000,000 years. The atomic weight of the lead is not known, but the ratio is highly accordant in the several analyses, suggesting that adventitious lead is probably low. The associated granites can not be older than the end of the Ordovician nor younger than the close of the Permian. By assigning them to the Taconic disturbance at the end of the Ordovician, a diastrophic movement which is known to have greatly disturbed the rocks immediately to the west, in the Hudson Valley, they are brought into this place in the column of maximum ages. In the column of minimum ages the Branchville uraninites fall in the early Devonian. If the presence of original lead should reduce the age to 360,000,000 or 370,000,000 years, the intrusion of the associated granites would fall into the Middle or Upper Devonian, times when granitic intrusions are known to have occurred in Nova Scotia and which were marked by notable diastrophism in the northern Appalachians, as reflected by the greatly stimulated sedimentation.

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[136] W. C. Brögger: Die Mineralien der Syenitpegmatitgänge der Sudnorwegischen. Augitund Nephelin-syenite. Leipzig, 1890, pp. 43-81.

[137] B. B. Boltwood: Am. Jour. Sci., vol. xxiii, 1907, p. 79.

The next older granite whose age is accurately measured by the lead-uranium ratio is that of Morogoro, German East Africa, giving a ratio of .093 and an age of 660,000,000 years. The atomic weight of the lead is 206.04, showing it to be wholly uranium lead. The age relations are, unfortunately, not definitely known.

The next determination in the sequence of age is that from a series of analyses from the Moss district of south Norway. The lead is wholly uranium lead, as proved by its atomic weight, and the large per cent of uranium gives high reliability to the result. The weighted lead-uranium ratio is .132, corresponding to an age of 925,000,000 years, the age of the post-Kalevian granites.

At a period still more remote in time occurs the most distinctive group of Precambrian granites. The percentages of lead and uranium from an analysis of a uraninite from Villeneuve, Ontario, have been recomputed by the writer, allowing for the two states of oxidation of the uranium. The result is somewhat different from that given by Holmes, the following figures being obtained:

$$\mathbf{Pb = 10.46,\ U = 64.74,\ Pb/U = 0.162}$$

in contrast to the ratio of 0.17 given by Holmes. From the Llano district in Texas a lead-uranium ratio of 0.167 to 0.170 was obtained as the most reliable. From the Arendal district in Norway a mean ratio of 0.168 to 0.169 has been derived by the writer by a reinspection of the original data. Holmes gives ratios for two other regions, but they depend on much smaller amounts of uranium. From Ytterby, Sweden, two ratios of 0.17 and 0.15 were obtained and two ratios of the same values were found for two localities in Mozambique.

These constitute the oldest reliable group of determinations and they show a remarkable concordance among themselves. A ratio of .165, corresponding to an age of between 1,100,000,000 and 1,200,000,000 years—more exactly, 1,125,000,000 years—satisfies the data from Canada, Texas, Norway, Sweden, and Africa. The geological relations show in Canada that the intrusions at Villeneuve belong to one of the Middle Precambrian granites—post-Sudburyan or post-Huronian. In the Arendal district the indications are similar, the granites being either post-Bottnian or post-

Kalevian. At Ytterby the intrusions are given as Ser-archean and equivalent in age to the post-Kalevian, but the Moss granites, with a well determined age of 925,000,000 years, are also post-Kalevian. The data for the Ytterby region are thus discordant, but they rest on two analyses in which the lead is given by Holmes as only 0.18 and 0.36 per cent, respectively, a lesser lead-uranium ratio and consequent lesser age being given by the higher and more reliable percentage. The Ytterby granites may then be provisionally regarded as not properly belonging to the group whose age is 1,125,000,000 years.

The number of determinations is not yet large enough to make it clear if the Precambrian granites over the world fall into a series of sharply defined groups. If they do, the decay of uranium minerals will give the most valuable method of Precambrian correlation. At present it appears that the group of granites whose geological position is designated as post-Kalevian, post-Huronian, or pre-Animikean is approximately 925,000,000 to 950,000,000 years old, and that the group variously designated as post-Bottnian, post-Sudburyan, or post-Temiskaming has an antiquity of 1,125,000,000 to 1,150,000,000 years.

Back of these lie still older granite-gneisses—the Laurentian system of Canada, the post-Ladogian of Fenno-Scandia—and these in turn were intruded into older sedimentary and effusive igneous series. It seems probable, then, that the oldest known rocks are as much as 1,400,000,000 years of age.

Beyond these most ancient milestones lies the Primordial era, whose stratigraphic record has been destroyed by engulfment in magmas from below and by repeated cycles of erosion from above. As to its length, there is no indication other than that the oldest known rocks which mark the beginning of the following era contain sediments which testify to an earth surface on which air and water played their parts, much as in later times. Crust, ocean, and atmosphere had by the opening of the Archeozoic already attained a condition of stability.

ADJUSTMENT WITH GEOLOGIC EVIDENCE

With these various control points more or less definitely established by means of the age of uranium minerals, a time table may be constructed for the eras of fossiliferous rocks, using the evidences of the quantity of erosion and of sedimentation to assist in establishing the relative lengths of the periods. The periods of a single era may be thus measured, but it has been argued that the mean rate of erosion and sedimentation for the several eras was quite different. In the stratigraphic records of the older eras there is, furthermore, a larger proportion of lost intervals.

Another line of control is given by the recurrences of crust movements which separate the periods. These pulse through earth history, apparently with some degree of regularity, and constitute the diastrophic basis for the division of the eras into periods.

The application of this principle may be seen in the Lower Paleozoic. From the basis of stratigraphy, the Cambrian and Ordovician are concluded, on the whole, to have been times characterized by widely flooded continents. The lands were restricted in area and low in relief, yet wide and thick limestone formations accumulated, indicating the passage of geologically long intervals of time. A better appreciation of the extreme length of these two periods is given by a close study of the diastrophic record. Schuchert and Ulrich, tracing out disconformities as revealing the coming and going of the epeiric seas, and delimiting the periods on this basis, have found that both Ordovician and Cambrian consist of several periods. On this basis Schuchert has recently subdivided the Ordovician into four new periods and the Cambrian into three.[138] This explains the unusual length, as given by stratigraphic evaluation.

Thus, adjusting the evidence regarding land area, relief, rate of deposition of sandstone, shale, and limestone, valuation of disconformities and unconformities, and fitting these to the ages determined by uranium minerals, there may be constructed a geologic chronology. This evidence is brought together in the following time table, the ratios for the periods being obtained from a series of papers by various geologists in which these have been individually estimated. A discussion of these ratios is next in order.

Dana, seeking the maximum thicknesses, taking each foot of limestone to be the equivalent of five feet of sandstone and shale, and assuming a uniform rate of accumulation throughout geologic time, obtained certain ratios for the successive periods. H. S. Williams, in 1893, taking into consideration the newer knowledge regarding the magnitude of Cambrian and Ordovician sedimentation, slightly modified these ratios,[139] his results being given in the following table, page 884. Walcott made at this time a careful study of the Paleozoic deposits of the Cordilleran sea and obtained a somewhat different set of figures,[140] the basis for which has been discussed in another section of this article. He did not attempt to give an estimate for each period, but dealt with the eras only. He considered that the relative lengths and the order of magnitude were satisfied by the following:

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[138] C. Schuchert: Correlation and chronology on the basis of paleogeography. Bull. Geol. Soc. Am., vol. 27, 1916, p. 496.

[139] H. S. Williams: The elements of the geological time scale. Jour. Geol., vol. i, 1893, pp. 283-295.

[140] C. D. Walcott: Geologic time as indicated by the sedimentary rocks of North America. Jour. Geol., vol. i, 1893, pp. 639-676.

Era	Time duration Years
Cenozoic, including Pleistocene	2,900,000
Mesozoic	7,240,000
Paleozoic	17,500,000
Algonkian	17,500,000
Archean	10,000,000 (?)

Schuchert, following Walcott's results for the length of the eras, published in 1910 an estimate of the proportionate time to be given to each period from the beginning of the Paleozoic.[141] These figures are listed in the following table, page 884. Lately, however, in a still unpublished manuscript,[142] he has revised his ratios and concedes a far longer duration for geologic time.

Sollas, in 1909, revised upward his previous estimates, giving 80,000,000 years as the most probable value of the age of the earth, as determined by the salt of the sea. He still estimated the duration of each period by means of the maximum thicknesses of sediments known in each, taking one foot as equivalent to a century and making up the balance of the 80,000,000 years by means of the time value assumed for unconformities. Following his method of measuring time by means of the maximum known thicknesses of sediments accumulated in each period, Sollas would with present data presumably raise the Jurassic to 2,000,000 years, since in northwestern Alaska the Cape Lisburne section shows about 20,000 feet of sediments, of which 15,000 bears plant fossils showing Jurassic age.[143] It would appear on this basis that the estimate for the Triassic might also be raised, since the very thick Newark deposits are restricted to Upper Triassic time.

The estimates by these geologists may be greatly magnified, but the ratios are nevertheless of value as expressing their judgment as to the *relative* lengths of the periods by those who have made special studies of stratigraphy. They have been made on a uniformitarian basis, with a knowledge of the limitations set by Lord Kelvin, and without reckoning in the significance of rhythms, but they must form a starting point for any revision of the duration of the several periods. These authors place more reliance on the relative length of the periods as expressed by ratios,

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[141] C. Schuchert: Paleogeography of North America. Bull. Geol. Soc. Am., vol. 20, 1910, plate 101.

[142] C. Schuchert: The earth's changing surface and climate. Chapter II of The evolution of the earth and its inhabitants. Yale Sigma Xi lectures for 1916-1917; to be published.

[143] A. J. Collier: Bull. U. S. Geol. Survey, Nos. 218, 259, 278, 1903, 1906.

NEW TABLE OF GEOLOGIC TIME

The following table shows the ratios for the geologic periods:

1.0 = 1,000,000 years

	Williams, 1893.	Schuchert, 1910.	Sollas, 1909.	Matthew, 1914.	Goodchild, 1896.	Barrell, 1917.			
						Minimum.		Maximum.	
						Each.	Total.	Each.	Total.
Recent	1	1.5	0.4	0.1	16.0	1		1.5	
Pleistocene							1		1.5
Pliocene	1		1.3	1.0		6	7	7.5	9
Miocene			1.4	3.0	77.4	12	19	14	23
Oligocene	1	1.5	1.2	2.0		16	35	16	39
Eocene			2.0	3.5		20	55	26	65
Cenozoic	*3.00*	*3.00*	*6.30*	*9.60*	*93.40*	*55*		*65*	
Cretaceous	4	2.7	2.4	.....	31.4	40	95	50	115
Comanche		1.8	2.0		72.6	25	120	35	150
Jurassic	3	2.25	.8			35	155	45	195
Triassic	2	2.25	1.7	.....	87.5	35	190	45	240
Mesozoic	*9.00*	*9.00*	*6.9*	*40.0*	*191.5*	*135*		*180*	

Permian	6	1.62	1.2	.....	45.0	25	215	40	280
Pennsylvanian		2.16	2.9	.....	31.8	35	250	50	330
Mississippian		2.70		.....	62.5	50	300	40	370
Devonian	5	1.98	2.2	.....	125.0	50	350	50	420
Silurian	4	1.80	1.5	.....	56.0	40	390	40	460
Ordovician	15	4.14	1.7	.....	57.0	90	480	130	590
Cambrian	15	3.60	2.6	.....	42.0	70	550	110	700
Paleozoic	*45.00*	*18.00*	*12.10*	.....	*419.3*	*360*		*540*	
Sum	57	30.00	25.3	.....	704.2	550		700	
Unconformities	.....	.....	14.7						
Round number	*60*	*30*	*40*	.....	*700*	*550*		*700*	

rather than on an absolute length as stated in years. Their results have been brought together in the following table and the ratios are given a numerical value such that unity represents 1,000,000 years as their best judgment. Their results have been carried out to fractions of a million years in order that the sums should be consistent, but the fractions have no other significance, since these authors have disclaimed a belief in the reliability of any such exact estimates of time.

The data from the various lines of evidence are assembled in the table, the conclusions being expressed in the right-hand columns. That designated the minimum is regarded as the more probable, but it is desirable to give maximum and minimum estimates in order to prevent a single column of figures conveying the idea of a precision or certainty which is not yet attained. The date of the opening of the Paleozoic is the most uncertain feature of this table because of the lack of uranium minerals of early Paleozoic age. Certain Precambrian dates are much better determined. These may be listed as follows:

Intrusion of post-Kalevian granites	925,000,000 years ago.
Intrusion of post-Bottnian granites	1,125,000,000 years ago.
Intrusion of post-Ladogian granites	1,400,000,000 years ago.

The oldest of these rests as yet, however, on very meager data.

The ratios of the length of the three fossil-bearing eras to each other approach more nearly to the ratios given by Walcott in 1893, followed by Schuchert in 1910, than to those given by others, but the absolute lengths which are assigned are from 18 to 22 times greater. These absolute lengths approach nearest to the estimates of Goodchild.

In regard to the Precambrian, a difficulty is encountered in giving appropriate divisions. It seems probable that on the same basis of crustal revolutions attended by notable granitic intrusion on which the later eras have been established, there may be as many as four Precambrian eras following the unknown Primordial time. As no settled opinion prevails, either as to the number of these eras, the best division points, or their names, and as the proper correlation of widely separated regions is still open to doubt, there is given here merely a list of the dates and consequent time intervals between points determined by granitic intrusion. The Fenno-Scandian nomenclature is used because the radioactive measurements have been somewhat more fully determined with reference to it.

As to the degree of accuracy of the table: First, the absolute ages depend fundamentally on the determination of the radioactive constants. It does not seem likely that future research will change the half-value period of uranium more than 2 per cent. They depend, secondly, on the presence of original lead or later alteration in the minerals by passing solvents or on analytical errors. The errors in these matters for some minerals have been shown to be small, under 5 per cent. For other minerals they may be several times as large. Third, the precise stratigraphic position is in many cases open to considerable doubt. This may introduce errors as high as 15 per cent of the total time. Fourth, the use of the stratigraphic ratios to supplement the radioactive evidence introduces another error affecting the ages of periods for which as yet no uranium minerals have been found. This may be rated as high as 15 or 25 per cent, but does not affect the determined points.

These several classes of errors are independent, so that to some extent they tend to offset each other. The divergence of the two columns marked minimum and maximum is intended to show about the latitude which the summation of the probable errors gives to the results, but, as stated before, the column of minimum figures should probably be given the greater weight.

CRESCENDOES IN DIASTROPHISM DUE TO COMPOSITE RHYTHMS

The distribution of time given in this new table brings out a notable regularity in the length of the periods, considering the Eocene and Oligocene to have the value of a single older period and the Cambrian and Ordovician as being equivalent to several of the later periods. The value of this rhythm of the periods ranges in general from 35,000,000 to 45,000,000 years, but the extreme limits are quite uncertain. The Comanche, for example, given a minimum length of 25,000,000 years, was a time of but moderate diastrophism. The rate of denudation may have been lower for it than for the adjacent periods, and if such were true the stratigraphic measurement of its length would give an underestimate unless the lower rate were considered. On the other hand, if the Mississippian, given here a length of from 40,000,000 to 50,000,000 years, should be subdivided into two periods, as Schuchert and Ulrich are inclined to hold, the length of these would appear to be not much greater than 25,000,000 years each.

The periods, 35,000,000 to 45,000,000 years in length, are delimited by epochs of notable diastrophism of an order of magnitude which Schuchert has named "disturbances." But the periods are subdivided by minor movements leading to "breaks" in the stratigraphic record, and are combined into larger groups constituting eras. The eras are terminated by periods in which the diastrophism is recurrent and reaches the proportions of a "revolution." The personal equation enters to a considerable extent in classifying the magnitude of these division lines, and a tendency exists to restrict, in thought, the crust movements to the end of a division, be it epoch, period, or era; whereas in reality the movements pulse through a division, the larger oscillations subsiding in the stage of quiet, rising in increasing pulses to that culmination which marks the close of one division of time, then subsiding through the initial portion of the following division.

The stages of crust movements, according to the nature of composite rhythms, are grouped into diastrophic crescendoes and diminuendoes. Thus in the great clastic formations of the lower Cambrian, laid down chiefly in geosynclines, we see recorded the decadence of a great period of revolution which terminated the Precambrian. The mudstones and sandstones of the upper Ordovician show a reawakening of internal forces which led to the Taconic disturbance or revolution. The Silurian was a period of quiet as compared to the Devonian, and the Mississippian was quiet in comparison with the Pennsylvanian and Permian. The comparative quiet of Triassic and Jurassic times led up in the close of the Jurassic to a diastrophic movement of marked proportions in the Cordillera which subdivides the Mesozoic era into an older and a younger division; but this was followed by the still greater diastrophism of the Cenozoic, awakening as the Laramide revolution, and rising to even greater magnitude in the Neocene.

Thus, there appears to run through geologic time a recurrence of greater crescendoes which in their average period approach in round numbers to 200,000,000 years. This is seen in the Precambrian, in that the post-Bottnian-pre-Kalevian era is found, apparently with accuracy, by means of uranium minerals, to comprise 200,000,000 years. The following post-Kalevian-pre-Paleozoic time, covering about 400,000,000 years, has important granite intrusions within it, and is marked in its earlier and later halves by contrast, in the nature of sedimentation, which serve to subdivide it. The Paleozoic, whose length is not well known, but which may comprise about 400,000,000 years, has been similarly subdivided, though the place and number of the division lines have not been chosen alike by all geologists. Dana used the end of the Ordovician as the place of separation, calling the earlier section the Eopaleozoic, the later section the Neopaleozoic. These sub-eras are broken into either two or three well marked groups of periods.

In so far as diastrophism serves as a basis for correlation, the Laramide revolution includes the Paleocene, Eocene, and Oligocene epochs and constitutes one period—the Paleogene or Eogene of Schuchert. It corresponds to the Pennsylvanian in the sequence of the Neopaleozoic periods. The Miocene, the beginning of the Neogene, witnessed the birth of the great Himalayan-Alpine mountain system from the geosynclines of ancient Tethys. Great movements took place also in western North and South America. The continents have been warped and the sealevel depressed in the Pliocene and Pleistocene to a degree not known to have occurred before since the earlier eras of earth history. Far-spreading glaciation and aridity have oscillated and rendered large areas of the lands almost or entirely uninhabitable. These conditions have by no means disappeared and the recent retreat of glaciation to high altitudes and latitudes must not be mistaken for the end of the period. In fact the upper Pleistocene appears to have shown a greater persistence of glaciation than was true of the middle or earlier parts of the epoch.

The Neogene should be used consequently as a term to include the Pleistocene and Recent, as proposed by Ulrich in 1911,[144] but its course should be looked upon as only one-half run. It is seen that the Appalachian revolution began with the opening of the Pennsylvanian period and pulsed through this and the Permian. The Laramide revolution began in the closing epochs of the Cretaceous, but it is only a part of a greater cycle of revolution whose convulsive phases have recurred with increasing magnitude through the Cenozoic, consisting of two periods, and whose end lies still hidden in the future, rather than revealed in the past. Comparing the march of diastrophism in the Cenozoic with that through the Carboniferous, beginning with the Pennsylvanian, it is seen that the present epoch, which the turning wheel of time will probably reveal to be but an interglacial stage of the Pleistocene, corresponds to about the middle of the Permian.

The Upper Cenozoic stands so close to us that we see it in detail, and conspicuously subdivided into epochs, emphasized by the rapid evolution of mammals; but the Permian was similarly subdivided, and if the Neogene were as remote from us in geologic time it would doubtless be seen in more accurate perspective in the whole history of the earth, as the period of revolution closing a great era which began with the Triassic. Taking the length of the Mesozoic from the minimum column of geologic time as 135,000,000 years, adding 55,000,000 years for the length of the Cenozoic and 10,000,000 years as yet to be fulfilled, gives to this whole Mesozoic-Cenozoic era a length of 200,000,000 years.

There is a human tendency, however, to seek for over-much regularity in nature and it is doubtful if much weight should be attached to this cycle of approximately 200,000,000 years. Although extremely suggestive of a new perspective, there are not enough terms, nor are they sharply enough defined, above those of lesser magnitude to give this indication more than such suggestive value. In regard to the lesser rhythms, consisting of the geologic periods and leading up to crescendoes of two or three geologic periods in span, the evidence is more clear. It is made apparent in this new time-table through the time-spacing which is necessary in order to bring adjustment between the radioactive and stratigraphic evidences. In such crescendoes, marking the liberation of forces pent up in the rigid body of the earth, we should not expect too much regularity of recurrence, nor similarity of expression, and yet such rhythms, the heart-beats of the earth-mother, running through her life-time, must serve as the great division points determining the crises in the evolution of the protoplasmic life which she has born.

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[144] E. O. Ulrich: Revision of the Paleozoic systems. Bull. Geol. Soc. Am., vol. 23, 1911, pp. 281-680; see pl. 26, p. 376.

A graphic representation of these composite rhythms in diastrophism, showing their rise into crescendoes, is to be published by Professor Lull, to which he adds the graph of the pulse of life.[145]

There are seen to be grounds for maintaining that, from the standpoint of diastrophism as a basis of correlation, the Recent is a part of the Pleistocene, and the Pleistocene an epoch of the Neogene period. The older Tertiary, or Paleogene, is a separate period, and both are divisions of the same order of magnitude as the four periods of the Mesozoic. They stand in somewhat the same relation to these earlier periods as the Permian and Pennsylvanian do to the preceding periods of the Neopaleozoic.

This brings out the difference between a classification founded on a diastrophic basis which begins an era with the *close* of a period of revolution and that founded on an organic basis. From the latter standpoint the Cenozoic, the Age of Mammals, is a separate era from the Mesozoic, the Age of Reptiles. But, for that matter, the reptiles date back into the Pennsylvanian. They seem there to occupy a place subordinate to the amphibians, but this is largely due to the fact that the coal swamps were the natural habitat of the amphibians; the drier uplands that of the reptiles. The sedimentation in the habitat of the amphibians accounts largely for the more abundant record of these lower forms. The aridity of the upper Mississippian must have been a stimulating cause, acting on ancestral amphibians, dependent on a life in water in embryonic and adolescent stages, which urged their transition into a class of vertebrates whose eggs were incubated in air and whose young dropped from their life cycle the gill-breathing of their ancestors.[146] During the Permian the reptiles clearly dominate over the amphibians and were differentiating into those orders which ruled the later periods. Thus, from the standpoint of vertebrate evolution the Age of Reptiles began in the Pennsylvanian, was established in the Permian, and ended with the Cretaceous. This is in fact the classification proposed by Ulrich[147] on the basis of diastrophism. The diastrophic and organic classification can then be brought into adjustment by placing the periods which mark crescendoes of diastrophism as the beginnings of new eras, not the ends of old ones. This is more logical and accords with the system of human history in which revolutions and their changed political conditions are placed as the opening events of new eras. It is doubtful, however, if this logical view will prevail in geology, since the older classification is solidly intrenched in the literature of a century.

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[145] R. S. Lull: The pulse of life. Chapter IV of the evolution of the earth and its inhabitants. Yale Sigma Xi lectures for 1916-1917.

On this new basis the Mesozoic, beginning with the Pennsylvanian and ending with the Cretaceous, would include 205,000,000 years on the minimum estimate of time, 270,000,000 years on the maximum estimate. The Neopaleozoic, embracing the Silurian-Mississippian periods, would include 140,000,000 or 130,000,000 years, thus falling short of the normal measure of an era. But the Eopaleozoic would include the revolution preceding the Cambrian. The Torridonian, Keweenawan, Beltian, and Grand Canyon systems, constituting the Lipalian era of Walcott, should apparently go into the Eopaleozoic. If the Morogoro granites of Africa, with an age of 660,000,000 years, mark a time in this Lipalian period of revolution characterized by continental uplift and continental deposits, then the Eopaleozoic also is delimited by a duration of 200,000,000 to 270,000,000 years, according to which scale of time is used.

MEAN RATES OF EROSION AND SEDIMENTATION

This table of geologic time carries several corollaries. The first to be noted is the mean rate of sedimentation for the several eras which would be required if the maximum thicknesses represented continuous sedimentation, as postulated by Sollas in his work previous to 1909 and by most geologists writing previous to the present decade. It has been argued in the present paper that this postulate is very far from being true, the very nature of sedimentation implying the presence of breaks of all orders of magnitude, the proportion of lost intervals increasing with the more distant eras. In the axes of maximum thickness, however, the discontinuities are reduced to a minimum. Recognizing that they still exist, it will be of value for comparison of the present conditions with the past to take the maximum known thickness for each era and divide it by the length of the era in years in order to get the comparative times represented by one foot of sediment. For this purpose the minimum ages given by uranium minerals will be used, as more probably of the proper magnitude. The tabulation follows:

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[146] Joseph Barrell: Origin and significance of the Mauch Chunk shale. Bull. Geol. Soc. Am., vol. 18, 1907, pp. 449-476; see pp. 469-474.

[147] Loc. cit., plate 26.

Geologic interval	Time interval Years	Maximum thickness Feet	Time for one foot Years
Pleistocene	1,500,000	4,000	375
Cenozoic	55,000,000	63,000	875
Mesozoic	135,000,000	84,000	1,600
Neopaleozoic	200,000,000	78,000	2,600
Eopaleozoic	160,000,000	43,000	3,700

It is seen that the rate of accumulation of the geosynclinal deposits appears to grow progressively slower with remoteness in time. There are several factors contributing to this effect in addition to the discontinuity which has been emphasized.

First. It has been shown that the Pleistocene has been a period marked by great orogenic movements and by high continental uplift, accomplished in a pulsatory manner. The Pleistocene, including the Recent, constitutes the culmination of a period of revolution, and the rates of erosion and sedimentation are both in consequence abnormally high.

Second. The stratigraphic record of the Cenozoic is fairly complete, since various deposits, largely continental, made above sealevel and geologically temporary, fill in the gaps represented by unconformities in other localities. Such a complete record could not be expected for an older era.

Third. As to the relative rates for the several eras, although the mean rate of erosion and sedimentation of the Tertiary should show less than the Pleistocene, the Tertiary, nevertheless, consists of two periods of revolution and its rate is naturally higher than that of the Mesozoic as a whole. There were long times of quiet and spreading seas in the Mesozoic when the surface processes must have sunk to a low rate. The blanks left by unconformities, furthermore, begin to play a larger part.

Fourth. In the Neopaleozoic the continents stood lower, as shown by a more prevailing spread of epeiric seas as compared to the Mesozoic. A low attitude of the continents reduces the area which is subjected to erosion and, even if the rate for the remaining land areas is high, the total volume of sediments per year for the whole continent is low. The sediments derived from a small land area are spread over a wide shallow sea and the rate of accumulation even in the geosyncline tends to be reduced, though the rate in the geosynclines depends more largely on the rate of subsidence.

Fifth. The relation of high sealevel to the vertical forces tending to maintain isostasy. When a continent is leveled with respect to a higher sealevel, the erosion of the smaller areas involves less isostatic strain toward rejuvenating uplift than if the whole continent were worn down to a lower level. Longer times of quiet may elapse and the movements toward equilibrium need not be so wide-spread nor violent as they must be for a greater depth between the isostatic level and the continental baselevel.

Sixth. The stages of lost record due to breaks of various magnitudes during sedimentation have already been mentioned. In addition to this, for the more distant times the record tends to become more imperfect, owing to the later events of geologic history. Some parts are uplifted and destroyed; others are mantled over with later sediments.

Seventh. It is possible that beside these factors which make for a low apparent rate in the Paleozoic, a real change may have taken place in the nature of the earth's internal forces. The later revolutions have been less profound than the great convulsions of the Archean, but diastrophism may make up for this by becoming more recurrent, tending to stimulate in post-Paleozoic eras the mean rate of erosion and sedimentation.

The stratigraphic record of the Precambrian is so fragmentary and imperfect that the preceding method of calculation is quite inapplicable. To gain some idea as to the mean rates of erosion and sedimentation which prevailed, recourse may be had to another line of argument. The Precambrian portion of geologic history shows regional metamorphism acting more than once on a world-wide scale. Molten rock welled up from the depths; part of it poured over the surface; other and greater parts did not reach the surface, but as abyssal magmas melted in, broke up, and engulfed the overlying crust. By aid of the escaping gases the cover rocks were crystallized. Compressive forces contorted and mashed them and led to recrystallizations, transforming both older and younger rocks into an intricate structure—the basement complex. Erosion planed sufficiently deep to expose these structures of the zone of rock flowage as the dominant type of Precambrian structures. In later ages such internal activities have been restricted to the belts of mountain systems. This contrast would seem to suggest that the Precambrian was characterized as a whole by more rapid, wide-spread, profound, and violent geologic activities, associated with the youth of the earth; but other lines of evidence to be discussed indicate that these revolutions were temporary conditions separated by long periods of quiet which have left almost no record.

The first line of evidence bearing on this conclusion is derived from the quantity of salt in the sea. It has been seen that the sodium would be derived from the weathering and erosion of a shell of average igneous rock about 2,300 feet thick, if enveloping the whole earth, or about 6,800 feet thick if derived from an area equal to the present continental platforms. It does not appear possible to materially modify these estimates. The greater part of present erosion consists in the reworking of sedimentary material, but since the opening of the Paleozoic it would appear from the large volume of the strata deposited that at least a third of this mile and a half shell of igneous rock must have yielded up its sodium. The implication is that Precambrian erosion was not by any means so profound, on the average, as the broad exposure at the surface of rocks originating in the zone of flow would suggest. It would seem that at times of great batholithic invasions regional metamorphism must have gone forward freely under a load of a mile or two of cover, the recrystallization being due to the great quantities of gas at high temperatures penetrating upward from underlying magmas. It has been found, in fact, for a number of far later batholithic invasions that they have approached so near to the surface as to be covered only by a slightly older mantle of tuffs and lavas of their own genesis; yet their texture is granitic and the cover rocks show extensive contact metamorphism.

If Precambrian erosion took place over an area greater than the present continental platforms, the mean depth of erosion of the igneous rock over this larger area was less than 6,800 feet. If the early erosive processes were less effective in weathering than in later times, then it would take a slightly thicker mantle to give rise to the oceanic salt. This factor tends to offset the one due to larger area of Precambrian lands, but is probably of much less importance. We may conclude, therefore, that the mean depth of erosion of average igneous rocks through all geological time has been less rather than over 6,800 feet. Let us grant the maximum available for Precambrian time, as this is leaning backward from the direction of the argument. Allow only one-fifth for later geological time, and the mean depth for the Precambrian erosion of igneous rock is still not more than a mile as a maximum figure.

The second line of evidence bearing on the problem is found in the peneplanation which occurred repeatedly, so that each Precambrian system was laid down on an almost level floor of older crystalline rocks. As compared to the scale of the initial relief following each revolution, the peneplain, even if hummocky, represents erosion to practical completeness. The development of such peneplains implies that the crust was stable and the earth rigid through long periods of time. Cooling, following each period of magmatic invasion, must have gone on to a very considerable depth, giving a temperature gradient perhaps lower than the present, and the deeper body of the earth may then, as now, have had throughout its present rigidity. These features alone show that Precambrian time was very long. The degree of evolution and differentiation of all the invertebrate phyla by the opening of the Paleozoic suggests also that the preceding time was as long as, or longer than, all subsequent time. The evidence from the uranium minerals comes now to support that view.

We are confronted, then, by several controlling conditions as to the nature of the Precambrian; the enormous duration of those ages, at least 700,000,000 years, perhaps 1,000,000,000 years; the wide-spread and recurrent igneous activity and regional metamorphism; the *average* depth for the erosion of *igneous* rock needed to reveal the Basement Complex over the continents not over a mile, and the existence of long periods of quiet and peneplanation. The long periods of quiet were comparable to the Cambro-Ordovician save that the continents in the earlier time tended to stand just above, rather than just below, sealevel. Instead of sheet after sheet of sediments being thinly spread, successive thin layers of rock were planed from the land—now here, now there—in addition to the removal of more limited tracts of higher plateaus and mountains.

The difference in geologic history between the Precambrian and the following eras was, consequently, largely due to the change in the mean sealevel; a slow change through a wider sweep of time than even those age-long tides which divide earth history into periods; a sweep so wide that all of geologic time has brought to pass only one completed rhythm, the continents now emerged from the Paleozoic seas suffering dominant erosion as in the remote Precambrian. But in other aspects the change is not rhythmic, but progressive; for the present conditions are, in many respects, not comparable: the ocean water has progressively increased in volume, but the continents have broken down into ocean basins in larger ratio. These causes are progressive and do not represent a return to primordial conditions, but the effects on the level of the sea have exhibited such a returning phase.

During the periods of plutonic overturn of the crust through the rise of magmas the rate of erosion for the uplifted areas may have exceeded the present rates for mountain regions, but during the long periods of quiet and peneplanation erosion must have sunk to a negligible amount. Slight oscillations downward would have stopped it altogether and have led to wide-spread and possibly long-enduring epeiric seas which have left no record, because a somewhat later sinking of the sealevel would have resulted in a washing of the previous deposits from the land.

The conclusion is so important that for better visualization it may be subjected to a quantitative statement in so far as the inexact nature of the data lends itself to such statement. The total volume of average igneous rock needed to supply the oceanic sodium is 84,300,000 cubic miles. This allows for the incomplete leaching of the igneous rock during erosion and sedimentation.[148] Take, as the extreme assumption, four-fifths of this as eroded in Precambrian time. This gives 67,000,000 cubic miles, the maximum which can be granted. Take the length of the Precambrian as 670,000,000 years, a minimum figure as given by uranium minerals. The result is an average of 0.1 cubic mile of igneous rock eroded per year—a maximum estimate.

To compare this average for the Precambrian with the present rate of supply of new salt to the sea, take the present area of igneous rocks as 20 per cent of the land area, or 11,000,000 square miles, as measured by Von Tillo. Take the present mean rate of erosion as one foot in 8,600 years, as given by the measurements of chemical denudation, and consider it to apply to the regions of igneous rock. This gives an erosion of .24 cubic mile per year of igneous rock.

A check calculation is given by taking the sodium uncombined with chlorine which is carried by the rivers to the sea each year. This is 69,000,000 tons. Let this be taken as a measure of the new sodium derived annually from the erosion of igneous rocks. In so far as new chlorine from volcanic action is combined with new sodium in the soil, this figure may be below the truth and tends to be a minimum. Now one cubic mile of average igneous rock will, by being subjected to erosion, yield 200,000,000 to 210,000,000 tons of sodium. The 69,000,000 tons of unchloridized sodium represents, then, the erosion of 0.33 cubic mile of average igneous rock. Thus we may take the mean of the two estimates and conclude that not less than 0.3 cubic mile is eroded per year now as compared to not more than 0.1 cubic mile as the average for Precambrian time.

But the present supply of new sodium is from only 20 per cent of the land area. In the Precambrian the average area of igneous rocks exposed was much greater, though at times considerable portions of the continents were covered in part by shallow sea and mantles of sediment. If the mean area of exposure of igneous rocks was then four times the present area.

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[148] F. W. Clarke: Data of geochemistry, p. 30, Bull. 616, U. S. Geol. Survey, 1916.

the mean rate of erosion of the Precambrian continents *per unit of area* was not more than one-twelfth of the present rate.

But it seems probable, first, that the Precambrian continents extended beyond the limits of the present continental platforms; second, that more than one-fifth of the erosion of igneous rocks has been accomplished since the Precambrian; third, that Precambrian time was somewhat longer than 670,000,000 years. The mean rate of continental denudation of Precambrian time was consequently not more than one-twelfth of the present rate and was perhaps not more than one-twentieth of that for the Pleistocene. This is a lower rate than was derived for the Eopaleozoic by means of the maximum thicknesses of sediments.

If at times of Precambrian revolution the rate of continental denudation occasionally reached its present amount and an area of three-fifths of the present continents consisted then of exposed igneous rocks, the annual destruction of igneous rock would have amounted at such times to about seven-tenths of a cubic mile. The total igneous rock destroyed in Precambrian times has been taken as 67,000,000 cubic miles. If the assumed maximum rate had continued, this total erosion would have been accomplished in 100,000,000 years, leaving nothing for all the remainder of the Precambrian ages. It seems clear, therefore, that the times of general continental rejuvenating uplift and denudation were very limited, occupying not more than a tenth of the time. Between these must have stretched long periods of quiescence, during which peneplains lay near baselevel and erosion subsided to a negligible minimum.

A low average rate of denudation for a continent may exist simultaneously with a far higher rate for the areas supplying the waste. Such a very low continental rate must have existed in the Eopaleozoic, since obviously when seas spread over the land the erosion rate for the flooded areas became even negative and must have been very small for the slightly emerged portions. For the Precambrian, however, the result is unexpected, since erosion proceeded over the continents at one time or another deeply enough to expose nearly everywhere a crystallized rock-floor. The low mean rate for these earlier periods brings into startling contrast two opposite aspects of Precambrian paleogeography—the almost interminable periods of quiet and peneplanation; the profound revolutions which separated them.

Such a period of revolution connected with broadly uplifted lands, diversified by mountain ranges and geosynclines, coursed by rapid rivers in a wide-spread network, occurred in the late Precambrian. Its formations are the continental deposits of the Keweenawan, the Torridonian, the Beltian, the Grand Canyon, and other systems—river deposits of semi-arid climates. But in the following era a new factor entered—a rising oscillating sealevel produced wide recurrent floodings of the lands and led to the deposition of the Eopaleozoic formations. But before that last Precambrian revolution occurred, an era passed away during most of which the lands must have been so flat that the deposits such as those of the Animikie were widely spread, and the streams must have meandered with stagnant flow over the low and restricted regions of erosion. Thus the Lipalian or Grand Canyon revolution looms forth in mountainous grandeur between a preceding and a succeeding world of low restricted plains and still more restricted uplands.

Lull has seized upon this contrast of physiographic conditions as a factor in the initiation of vertebrate evolution. During the period of peneplanation the sluggish currents which marked the physical environment would not have required sustained movement in floating animals of either the seas or rivers in order than they should remain within their habitat. With the opening, however, of a period of revolution the continents were uplifted, the domain of the fresh waters would expand and they would take on a rapid flow. The freely moving animals of these waters would now have to become vigorous swimmers if they were to stem the currents and survive within their fluviatile environment. Lull regards this environmental stimulus as apparently essential for the development of the initial fishlike forms of the early chordates, adjusted thus to the flowing fresh waters and leading to the establishment of their dynamic superiority over other phyla. From first to last the chordates have thus found their central field of evolution on the surface of the continents—at first within the flowing waters, later as true terrestrial vertebrates.

Thus, through the recognition of these wide variations in environmental conditions leading from age to age out of the remote geologic past, supplanting a picture of monotonous uniformity, the progress of evolution is perceived to have been attained by pulses. Tracing this surge of cause through geologic time and detecting its effects in the progress of organic evolution, Lull has written "the pulse of life."[149]

By far the greater portion of the Precambrian consisted of periods of comparative quiet. These, as shown, must have been more than ten times longer than the periods of revolution, but we see them represented chiefly by surfaces of unconformity, whereas the revolution thrusts its existence before the imagination through the evidence of igneous activity and metamorphism—of mountain structures and consequent rapid erosion and deposition. These periods of wide and profound disturbance, lying in the background of earth history, because of their very remoteness are projected into one sphere of vision. Perception of distance and perspective are lost—as in the stars which spangle the firmament, showing by their radiance their fiery activities, but giving no suggestion of the vast spaces of empty cold which lie between.

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[149] R. S. Lull: The pulse of life. Chapter IV of The evolution of the earth and its inhabitants. Yale Sigma Xi lectures for 1916-1917; to be published.

R. S. Lull: Organic evolution, 1917, section 3. Paleontology, pp. 409-691.

RELATIONS BETWEEN LAPSE OF TIME AND ORGANIC EVOLUTION

Closely connected with this expanded view of terrestrial duration is another problem which in conclusion should be touched upon—the relationship of geologic time to the progress of organic evolution.

If life originated at an early period on this earth and was not derived from germs driven by the pressure of light from other worlds, protoplasm must have existed at first as mere molecules of very complex nature. Possessing a power of assimilation, such molecules became colloidal aggregates by virtue of adding to their substance, at first totally without structure or differentiation. In our ignorance of the ultra-microscopic stages of organization which lie between the protoplasmic molecule and the visible structures, we are prone to slight the necessity for the evolution of these stages which led up to the organization of the cell; yet in these the foundations of all later progress were laid. Protoplasm had to become differentiated and organized, chemically and physically. There had to arise nucleus, cytoplasm, and cell wall; powers of photosynthesis, of digestion and excretion, of irritability and contractility. This chemical organization represents an adaptation to environment which must have resulted from the selection of efficient variations out of numberless chance chemical combinations. The initial preservation of the successful protoplasmic combination was owing to the fact that the world was as yet without predatory organisms.

Most remarkable of all, perhaps, in this basal evolution was the establishment of the principles of inheritance, residing in a marvelous mechanism, by virtue of which the descendants start life with the capital of efficiency acquired by their ancestors and sifted by selection through all previous time. Without inheritance there could be no progress, but powers of inheritance mean an incomprehensible complexity in the ultramicroscopic structure of the cell. The chromatin threads in the single, undifferentiated metazoan egg-cell determine the differentiation and assemblage of the billions of daughter cells which build the adult body. Considering the stages which have to be passed through, the child is marvelously like the parent; the wonder is not that there is so much variation, but that there is so little. Yet this development of the metazoan is only a higher expression of powers already evolved in the protozoan. The evolution of the habits of conjugation, of the exchange and combination of Mendelian factors, of the habits of precisely similar growth generation after generation, are all parts of a protoplasmic machinery which had to become established before even protozoan progress was possible. This machinery could not rapidly evolve. Like all later advances, it must have been the result of numberless variations, the efficient sifted out by the elimination of the unfit. It would seem that the vast length of the early Precambrian ages was none too long for the accomplishment of this half of evolution of which we know so little.

Turning to a better known side of the subject, the evolution of the vertebrates; the geologic record shows that the great advances coincide with changes in environment. The advances represent modifications of older structures and their combination to new ends and with increased efficiency. The variations must come from within by modifications of the germ plasm, and these, once established, are carried forward and perpetuated through the stability of inheritance. But the efficient variations, representing improved adaptations to a changing environment, must be sifted out from inefficient and degenerative variations by natural selection leading to the survival of the fittest. The same principles doubtless led to the long upward journey in the organization of the protozoa.

If evolution were due only to internal changes, to the mere sloughing off of inhibiting Mendelian factors, it might proceed with rapid pace; but if, as the geologic record testifies, it waits on environmental change and requires a transformation of unrelated organs with mutual support and efficiency, as seen in the organization of lungs, circulation, and limbs—needed to transform the fish into the amphibian—then evolution must proceed with surpassing slowness. Millions of generations must cross the stage of life to furnish again and again the chance combinations which are seized on by nature at times when the environment exerts a critical and selective pressure. These forces which make for evolution work intermittently, not continuously. Degeneration rather than evolution is the result where nature ceases to drive and organisms are left to procreate freely.

Viewed in this light, it seems impossible to compress the evolution and deployment of Cenozoic mammals, gained through the march of many successive faunas, into any such limited time as 3,000,000 years. Ten times this seems none too long. In fact, fifty or sixty million years, giving perhaps from ten to twenty million generations, may have been needed for the transformation of the generalized mammal of the basal Eocene through the many successive faunas into the varied life of the living age.

Lyell regarded 20,000,000 years as a probable length of a geologic period required for the transformation of species. Darwin thought 200,000,000 years too short for the accomplishment of organic evolution. It would appear that they were conservative in these expressions of opinion and that this expansion of geologic time should be welcomed by the biologist as well as by the geologist.

BEARINGS OF GEOLOGIC TIME ON THE PROBLEM OF STELLAR ENERGY

The length of geologic time has a highly significant bearing on the nature of the supply of the solar radiant energy, and, as the sun is but one of the host of stars, it has a wider bearing on the whole problem of the sources of stellar energy and the course of stellar evolution.

Until the discovery of radioactivity, there seemed to be no conceivable adequate source for the enormous expenditure of solar energy save in the contraction of the sun's mass, transforming the energy derived from gravitational infall into radiant energy. A present shrinkage in radius amounting to 200 feet per year would be sufficient to liberate enough energy to balance the expenditure. On this basis Helmholtz calculated in 1856 that if the sun had in past time delivered heat at its present rate that it could not be more than about 20,000,000 years old. Kelvin, by introducing the condition that the sun is probably very much denser in its interior, considered that the age might be somewhat greater. Ritter, Tait, and certain other physicists held, however, that the earth's organic history could not have extended beyond 10,000,000 or 12,000,000 years.

In view of these very restricted limits, attempts have been made by various men to draw on the internal heat of the earth as a supplemental supply. It has been argued that such a source would account in earlier times for the equable climates and the absence of marked zones. A thick atmosphere, moist and rich in carbon dioxide, is a further postulate, serving as a blanket to hold in more effectively the internal heat and maintain a higher temperature of the surface.

There are several serious obstacles to the acceptance of such a hypothesis as an important factor in paleoclimatology.

First, the amount of radioactivity known to exist in the crust appears adequate, or more than adequate, to account for the whole emanation of heat. There is no evidence, therefore, that the earth is cooling and that the crust gave forth more heat in earlier times.

Second, the deeper parts of many Precambrian formations, such as the Unkar and Chuar exposed in the depths of the Grand Canyon of Arizona, have been buried to a depth of several miles in the late Precambrian, and again in the Paleozoic, and yet show no regional metamorphism, comparing in this respect with Paleozoic and Mesozoic formations. The temperature gradient since the late Precambrian could not, therefore, have been notably higher than the present.

Third, the quantity of heat which the earth delivers to the atmosphere is now and must always have been inconsequential in comparison with that derived at present from the sun. For instance, to have conducted five times the heat, the temperature gradient would have to be five times as steep, giving a temperature of molten rocks at a depth of five miles.

Fourth, the presence of banding in certain argillites of early Precambrian times in Norway and Canada, associated with ancient glacial deposits, is directly comparable with the annual banding in stratification in Pleistocene clays in those same regions, and testifies to the dependence of temperature in those times on solar radiation with an atmospheric condition which permitted the existence of winter.

Fifth, the abundance of carbon in the clays of early Precambrian time suggests the presence of sunlight sufficient to carry forward photosynthesis in plants and therefore the absence of an extremely dense cloud envelope.

Sixth, glacial conditions are found to be associated with times of terrestrial revolutions closing the eras and to have recurred at times since the Middle Precambrian. Similarly, periods of wide-spread aridity have recurred at intervals since the Upper Precambrian. The composition of the atmosphere and ranges of temperature have, therefore, been subject to fluctuation through all geological time and have not shown a steady decline, formerly suggested as a cause for Pleistocene glaciation. The normal existence of warm temperate climates in high latitudes and the Permian glaciation in low latitudes must therefore rest on some other explanation.

Consequently, we must return to the conclusion that the sun through all geological time has been the only effective source of terrestrial warmth. But life began to evolve in the earliest known times, and since then the temperature limits compatible with the continued existence of the various classes of organisms have never been exceeded. When it is considered how narrow these limits are, as compared with the absolute cold of space on the one hand and the temperature of the sun on the other, it is seen that not only has the sun radiated energy through all geological time, but that the flow of energy, although subject to rhythmic fluctuations, has been nearly constant. This constancy suggests that the sun was already past the formative period in the earliest times for which there is a geological record and has not yet entered into the declining stages of its history. In view of these facts, it is seen that even for an age of 50,000,000 years the hypothesis of solar energy due to gravitational infall seems hopelessly inadequate. What, then, shall be said of an age as great as 1,500,000,000 years? It is of the order of one hundred times too great. The issue is sharply drawn and indicates that either geological time has been overestimated a hundred fold or the hypothesis of self-contraction as the source of solar energy does not account for more than perhaps 1 per cent of the expenditure.

This problem has been discussed also by Holmes.[150] Rutherford and Soddy in 1903 pointed out the possible importance of radio-thermal action in the sun, but Wilson in the same year showed that, if the sun were wholly composed of uranium and thorium in equilibrium with their disintegration products, the radioactive disintegration, although ample in duration, would give rise to only a fraction of the daily expenditure of solar energy. Holmes finds, on account of the slowness of these transformations, that by no possibility could more than one-third of the sun's heat be accounted for by the radioactivity of uranium and thorium. Either, then, there are further atomic disintegrations which supply more heat or, as Arrhenius has suggested in more general form, there are higher stores of energy which may be liberated by changes in physical states at high temperatures and great pressures, latent heat being given out as thermal energy by their transformations.[151] Of course, such suppositions only emphasize our ignorance of the cosmic process, for before this energy can be liberated it must in some manner have been stored. For example, the enormous energy liberated by the stepping down of uranium, with molecular weight 232.2, into lead of molecular weight 206.2 must previously have been absorbed in the building up of uranium. The lead in its origin has presumably still stored within its atom much more energy than is liberated by its generation from uranium.

Such intra-atomic energies may be inferred for the elements which are not radioactive from analogy with those that are and also from the higher incompressibilities of the elements of small atomic volume. An external load only slightly condenses the sphere of influence which may be regarded as the volume of the atom, and the work of condensation is absorbed as an added store of energy. The coefficient of expansion is also small and indicates that the energy of the absorbed heat only slightly expands the sphere of the atom's influence. The internal fixed energy of the atom is therefore enormous as compared with that which can be added or taken away by processes under human control.

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[150] Arthur Holmes: The age of the earth, 1913. Chapter VIII, the thermal energy of the sun.

[151] Svante Arrhenius: The life of the universe, vol. ii, chap. viii. The energy conception in cosmogony, 1909.

In some manner the elements must have had their evolution, and according to the law of the conservation of energy that which the stars are now liberating must first have been absorbed. The apparent running down of the visible universe must be but one phase of a recurrent cosmic cycle philosophically necessary in infinite time, or else the running down would have been completed in previous eternity. The nature of this cyclic process is still far beyond the bounds of scientific investigation. It was thought that in gravitational infall an adequate explanation had been found for one phase of the cycle, that of the liberation of the radiant energy of the stars; but the quantities dissipated by the sun through the vast length of geologic time indicate that the contraction of the solar mass can not be more than a minor factor in the conversion of its energy.

The scheme of the universe is more profound and the unknown is a little nearer than it was recently thought to be. But such has been the progress of knowledge since man, in the days before the advent of science, naively regarded the earth, his home, as the center of the universe and the heavenly bodies as lights in a near-by firmament, created a few thousand years previously especially for his benefit.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 28, PP. 905-916 DECEMBER 14, 1917

DIAGNOSTIC CHARACTERISTICS OF MARINE CLASTICS[1]

BY E. M. KINDLE

(Presented before the Society December 29, 1916)

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INTRODUCTION

"A more accurate and quantitative knowledge of that earth history which is now being recorded is needed in order to obtain in turn a more accurate knowledge of the past." This statement, quoted from Professor Barrell,[2] is important enough to be repeated and put in the form of an admonition to geologists which might be framed thus: "Know well the present before crossing the threshold of the past." I have attempted in recent years, so far as circumstances and official duties would permit, to carry out in some measure the spirit of this admonition. Some of the scraps of information which I have gathered while trying to understand present-day processes in geology have a bearing on the subject which has been assigned me. These will be offered for your consideration frankly as fragmentary materials and suggestions for the precise definition of the criteria of marine clastics which will be written some time in the future.

Any discussion of the criteria which characterize marine clastics may well begin by noting the great contrast in composition which distinguishes marine from fluvial and lacustrine waters. This difference con-

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[1] The third of a series of papers composing a "Symposium on the Interpretation of Sedimentary Rocks."

Manuscript received by the Secretary of the Society April 10, 1917.

Published with the permission of the Director of the Canadian Geological Survey.

[2] J. Barrell: Criteria for the recognition of ancient delta deposits. Bull. Geol. Soc. Am., vol. 23, 1912, p. 446.

sists chiefly in the presence of 2 to 3 per cent of salt in marine waters and its nearly complete absence from continental waters which are not land-locked.

The outstanding biological fact connected with the contrast in composition between marine and fresh waters is the amazing fertility of the sea in life and the relative poverty of fresh waters.

The fecundity of the sea, as illustrated by a mussel bed with "a population of 16,000 mollusca to every square foot,"[3] is nowhere paralleled or approached in fresh waters. The salinity of marine waters results, as is well known, in a complete difference in the kind as well as the quantity of life characterizing marine and continental waters. So sharp is the biologic contrast that where fossils are preserved in the rocks no further criteria, as a rule, are needed to distinguish marine from continental deposits. In both marine and non-marine formations, however, fossils are often absent or so rare as not to be available in interpreting the geological history. It is therefore most desirable that we should endeavor to understand and interpret the physical record where the biological record fails us.

The very fact that salt and fresh waters yield such strikingly different forms of life at once suggests the probability of commensurate differences in the physical characters of the rocks formed in fresh and saline waters. It may be easily demonstrated experimentally that many kinds of sediment behave very differently in these two kinds of waters.

Relative Rates of Deposition in saline and in fresh Water

The surprisingly different rates at which sedimentation proceeds in fresh and salt water is a fact of importance in seeking for the distinctive features which may be expected to characterize marine rocks. This difference may be easily demonstrated by introducing an aqueous mixture of any fine clay into each of two beakers containing respectively saline and fresh water. The sediment introduced into the salt water will reach the bottom in a few minutes, leaving the water above it clear. In the fresh water much of the sediment will remain in suspension for an indefinite period and the water may be turbid for weeks or months. According to Professor Brewer,[4] even several years may not suffice to complete the sedimentation in the case of some kinds of sediments.

In order to study the differences which mark the processes of sedimentation in fresh and saline waters, two sets of experiments were carried out in an experimental tank. These were designed to show the contrast in the character of beds laid down where salinity was the only factor which differed in the two experiments. Fresh water was used in the first and salt water in the other experiment. In both cases clay, powdered chalk, and sand were introduced in the same order and amounts, and the same time intervals for settling were allowed. The materials were introduced in the form of aqueous mixtures by means of a small stream of water pouring slowly into the settling tank through a tube. The results of the two experiments are shown in the two photographs reproduced as figures 1 and 2. Figure 1, which represents the tank with saline water, shows a series of sharply defined beds, consisting of three bands of clay separated by two beds of chalk and a bed of sand terminating the section. In figure 2, although the same materials were used in the same quantity and order, the resulting section is materially different. Even the order of superposition is different. The sand, instead of lying at the top of the section, lies below the top, under a half-inch bed of clay, although the clay was introduced several hours before the sand. The fresh-water section thus fails to indicate the true order in which the

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[3] James Johnstone: Conditions of life in the sea, 1908, pp. 176-177.

[4] William H. Brewer: On the subsidence of particles in liquids. Memoirs Nat. Acad. Sci., vol. ii, pp. 163-175, 1884.

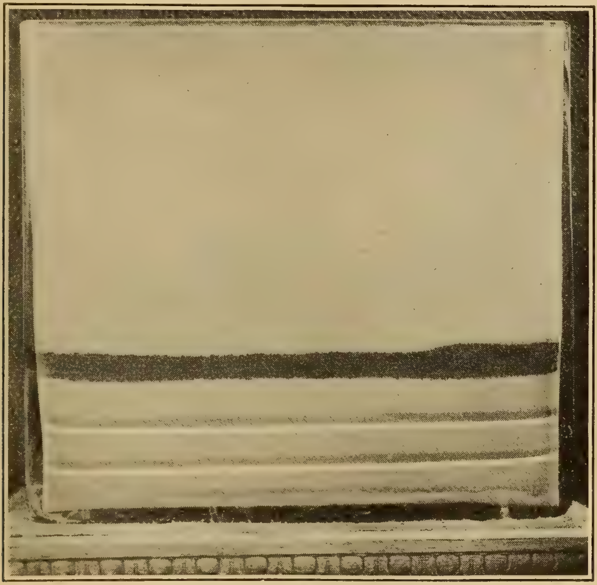

FIGURE 1.—*Photograph of a Section formed in salt Water*

The section, as seen through the side of the glass tank, consists of three beds of clay, two beds of powdered chalk, and a bed of sand at the top of the series materials were brought into the tank. Instead of the beds of pure white chalk and clean sand afforded by the saline sedimentation, the fresh-water tank has given drab-colored chalk bands mixed with clay and a band of muddy sand. The wavy contrast between the base of the upper chalk and the clay is due to a slight acceleration of the current and the consequent development of vertical currents on one side of the tank during the introduction of the chalk. It has no direct relation to the matters here discussed, but illustrates a peculiar type of structure which may result from semivertical or rotating currents which carry sediment into a body of quiet water. These two experiments show that the tendency of marine sedimentation is toward sharply contrasted beds, while fresh water tends to give beds in which different classes of sediment are not sharply segregated, and to furnish comparatively slight contrasts in kinds of strata. The application of this principle in discriminating between marine and continental deposits could be wisely made only by giving due consideration to various other factors which might enter into the individual problem. In general, however, it would appear safe to infer a marine origin for any series of beds in which pure sandstones and shales or limestones were characteristic and sharply defined elements. On the other hand,

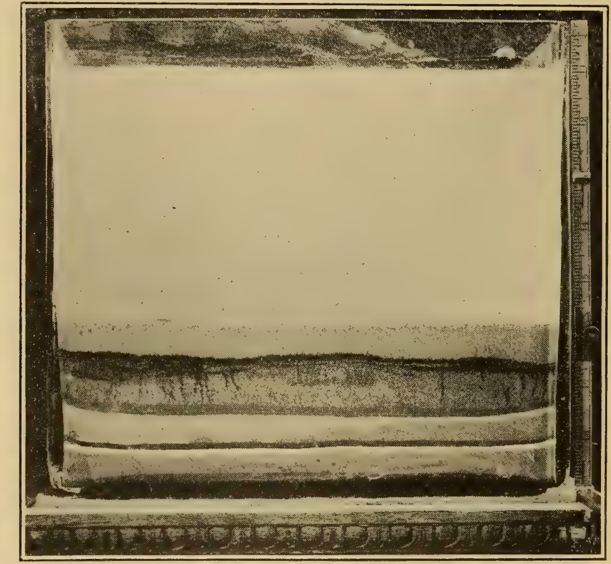

FIGURE 2.—*Photograph of a Section formed in fresh Water.*

The same materials in the tank introduced in the same order and amount as those used in developing the section shown in figure 1. Note the different order of superposition of the sand and clay in the two figures.

any extensive series like the Catskill beds of southwestern New York, in which argillaceous sandstones and sandy shales are conspicuous elements and pure limestones wanting, might properly be suspected of having originated in fresh water.

Structures developed in marine Beds

The rapidity with which deposition of fine suspended matter proceeds in marine water under favorable conditions of supply of sediment leads to the phenomena of vertical currents, which in the case of fine muds may leave a characteristic and distinctive imprint on the material laid down which will distinguish it from fresh-water sediments.[5] These structures, which may be termed pit and mound structures, may be developed experimentally by adding to a glass containing an aqueous mixture of fine clay a pinch of salt. The flocculation of the clay which follows the addition of the salt will be accompanied by the development of numerous vertical currents. These currents develop chimney-like channels through the

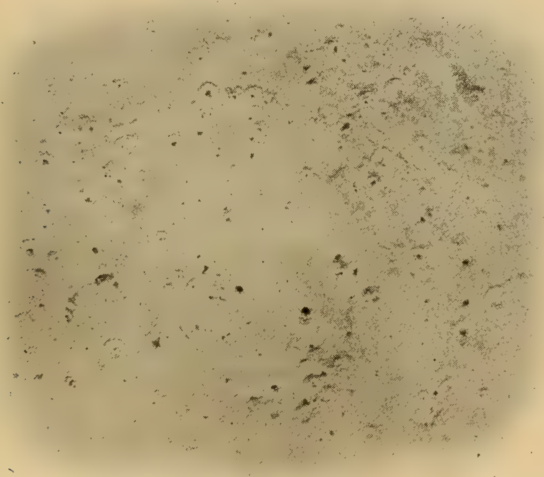

Figure 3.—*Pit and Mound Structures developed on the Surface of water-laid Sediment by vertical Currents*

About natural size

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[5] E. M. Kindle: Small pit and mound structures developed during sedimentation. Geol. Magazine, vol. iii, Dec. 6, 1916, pp. 542-547, pl. xiii.

Note.—In a review of this paper (Ind. Alum. Mag., vol. 4, p. 429, 1917), Prof. E. R. Cummings reports having observed numerous examples of these structures in the Richmond formation of southern Indiana.

subsiding sediment, and around the tops of these channels small mounds or pits are formed. These are shown in the accompanying photographs, figure 3. Sometimes, instead of either of these, pin-head depressions appear over the surface, but beehive-shaped protuberances with a small opening at the top are the most common. Under ntaural conditions these vertical currents would probably be effective in developing surface features on the sediments only where deposition was very rapid, as near the delta area of a large river. Where the deposition of mud is going on at the rate of 12 inches in four days,[6] as has been reported by Kellog on parts of the Gulf coast, the features which have been described would be very likely to be developed. Wherever these peculiar and characteristic impressions can be detected on rocks they should furnish evidence of their origin in saline waters as conclusive as that afforded by rain-prints of the subaerial origin of the beds in which they occur.

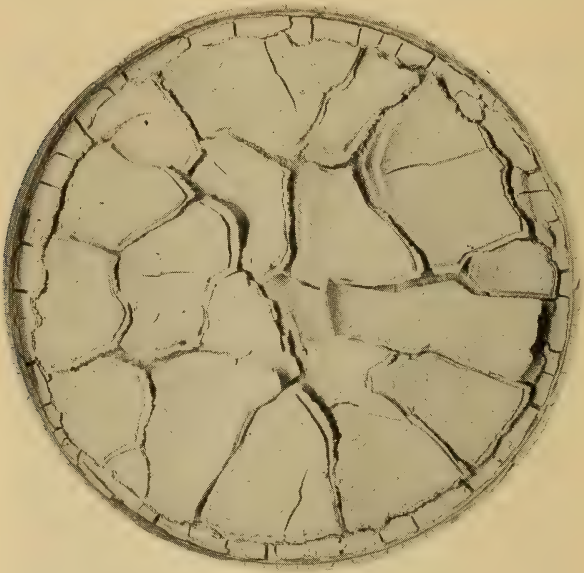

FIGURE 4.—*Mud-crack showing the upwarped Margins of Polygons*

This is a characteristic of fresh-water mud-crack

EFFECT OF DESICCATION ON SALINE AND ON FRESH-WATER MUDS

The evidence of mud-cracks may in some cases be of value in deciding whether a given terrane is of marine or continental origin. Mud-cracks and the sediments cut by them, when formed on the seashore within the tide limits, are a product of marine conditions and belong logically to the phenomena of marine sedimentation. Under favorable conditions they may differ from those formed in fresh-water mud as definitely as do the fresh-water and salt-water shells. Experiments in desiccation carried out by the writer have shown that the polygons formed in fresh-water mud have a marked tendency to warp up at the margins (figure 4). In saline mud the polygons remain flat or warp downward at the edges. The latter tendency has been noted only in very saline muds. Figures 5 and 6 show the marked contrast in the behavior of desiccated salt and fresh-water mud.

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[6] Louisiana Gulf Biological Station, Bull. 3, 1905, p. 37.

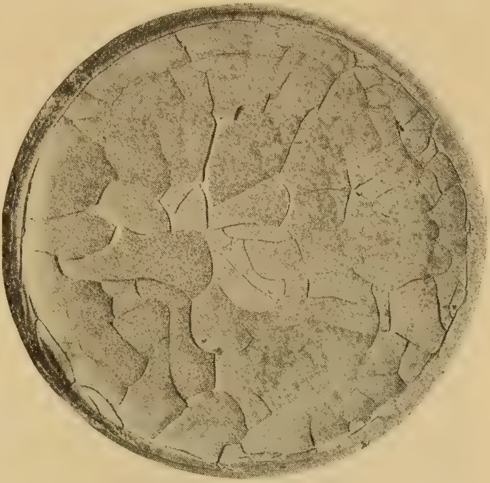


FIGURE 5.—*Mud-crack showing Polygons slightly downwarped at the Margins*

A characteristic of mud-crack in very saline mud

In the case of fossil mud-cracks the geologist can make definite deductions regarding the salinity of the original mud only where there has been distinct upwarping or downwarping of the polygons. Where the surface is flat, as is usually the case, lack of warping might as likely be due to the tenacity of the mud overcoming the upwarping tendency characteristic of fresh-water mud-crack polygons as to the normal tendency of the salinity of the sea-water to produce flat polygons. Where the polygons show a definite saucer-like upwarp at the margins, however, the inference that they were formed from fresh-water mud and represented continental sedimentation would be inevitable. I

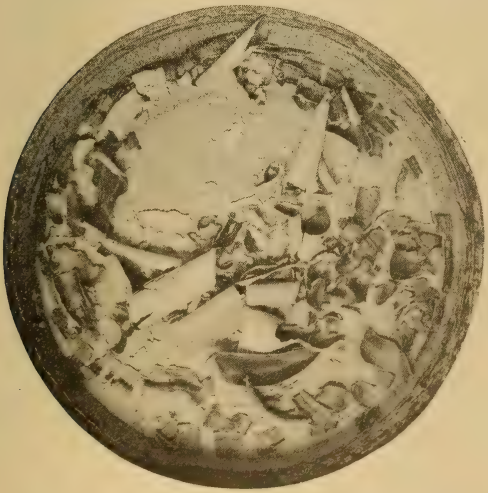
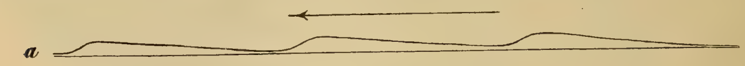


FIGURE 6.—*Fresh-water Mud-crack with Polygons*

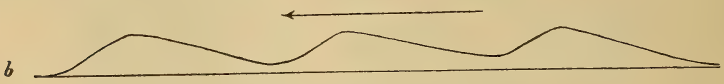
Showing an extreme degree of upwarp

have described[7] from bed A of the Mount Wissick section in New Brunswick an example of this kind which, in the light of these experiments, must be referred to continental or fresh-water conditions, although I originally supposed it to have been formed on a tide flat.

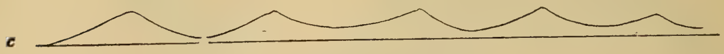
Contrast in texture is another feature which may sometimes aid in discriminating desiccated marine from fresh-water clastics composed of fine-grained materials. The former show in many cases a vesicular and the latter a compact non-vesicular texture. An interesting feature generally shown by experimental desiccation of saline mud is the presence throughout much of the material of numerous minute cavities. These cavities were first noted in experimenting with the Pleistocene blue clay of the Ottawa Valley, in which they had usually a diameter of from one-third to one-half millimeter. Desiccated mud made with fresh water from the same clay showed no trace of the cavities, thus indicating that this feature was due to the presence of the salt. This remarkable contrast between the texture of desiccated mud containing salt and the texture of dried mud free from salt was verified by a number of tests in which clay from the bottom of Lake Ontario was used. In these tests duplicate lots of mud were desiccated in vessels of the same size, the same quantity from the same mixture being used in the parallel tests. The salt which was added to one sample in each case was the only factor which was allowed to differ in the two lots. In each case the dry saline mud showed numerous small cavities which were absent in the corresponding sample of fresh-water mud. Considerable geologic interest attaches to this feature because it is one which would in many cases almost certainly be preserved permanently in the rocks. It should therefore furnish, in the case of



Air current ripple-mark



Water current ripple-mark



Wave ripple-mark

FIGURE 7.—*Diagrammatic Illustrations of Ripple-mark Types*

fine-textured clastics deposited under subaerial conditions, decisive evidence as to whether they originated near the seashore or were of fluviolacustrine origin.

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[7] Can. Geol. Survey, Mus. Bull. 2, 1914, p. 37.

Ripple-mark

The familiar phenomena of ripple-mark merits consideration in any study of the criteria of marine clastics. Any appreciation of the significance of ripple-mark must begin with a clear discrimination of the two common types of ripple-mark and of the agencies which produce them. These are the symmetrical and asymmetrical types. They are produced respectively by wave and current action. The distinctive characteristics of the two types are shown in figure 7, *a* to *c*. Because of their diverse modes of origin these two types become absolute criteria for differentiating current-laid from wave-assorted sands. Current action, owing to the tides, is a daily feature of nearly all coastal marine waters, and leaves its characteristic type of ripple-mark (figure 8), while it is a comparatively rare feature in lacustrine waters. Wave action, of course, is common to both. But the symmetric wave ripple-mark, when produced on the sea-bottom, is apt to be obliterated by the daily tidal currents, which thus have a far better chance of preservation near the seashore than has wave ripple-mark. Further, wave ripple-mark (figure 9) can be formed only at limited depths, while current ripple-mark has no depth limit. It follows, therefore, that an enormously larger area of sea-bottom is subject

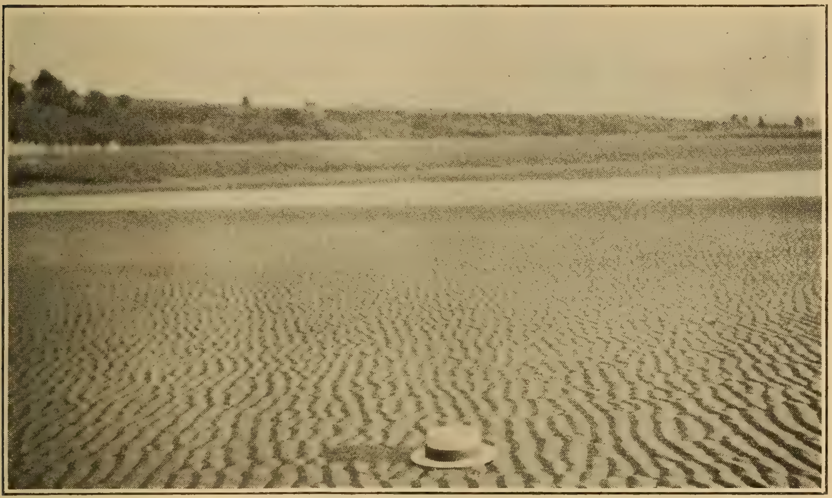

FIGURE 8.—*Ripple-mark produced by Current Action*

This locality is the estuary of Avon River, Nova Scotia to ripple-mark of the current-made type than to the wave type of ripple-mark. It is clear from this that asymmetric ripple-mark (figure 8) is the type commonly preserved in marine depths, while the symmetric type has a comparatively small opportunity for preservation in marine clastics. In lacustrine deposits, on the other hand, the opposite is true. The almost daily activity of waves and the comparative rarity of current action gives rise to the great dominance in such deposits of symmetrical wave-mark. Even in fluvial deposits sedimentation takes place for the most part in times of great lateral expansion of the stream, when its conditions, as regards lack of notable current, are essentially lacustrine. Under these conditions the great bulk of fluvial deposits would, if ripple-marked, show the symmetric type of ripple-mark (figure 9).

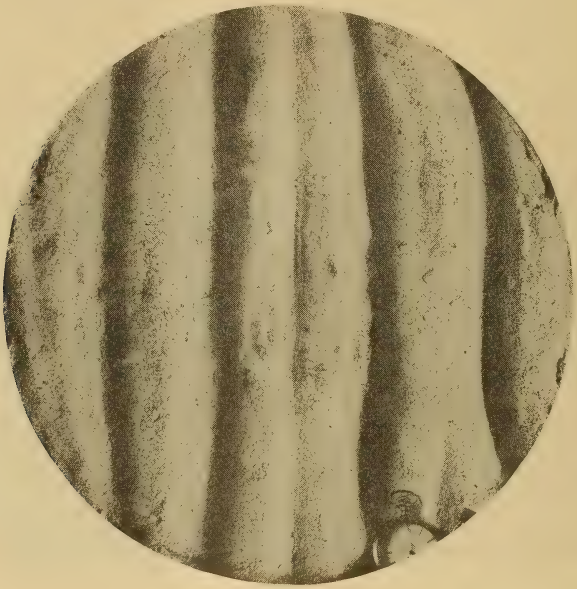

FIGURE 9.—*Plaster Cast of Ripple-mark formed by Wave Action*

The photograph is of the bottom of Lake Ontario near Wellington

From these considerations it appears that the asymmetric type of ripple-mark, when it greatly preponderates over the symmetric type in any set of beds, may be regarded as pointing strongly toward their marine origin.

To this use of ripple-mark in discriminating between marine and continental clastics, the objection may be raised that river deposits found within the limits of the channel will be characterized by the current type of ripple-mark which is not distinguishable from that formed by tidal currents. This objection, however, overlooks the important fact that the direction of the river current is invariable, while the tidal current reverses its direction twice daily. Consequently all of the current ripple-mark in a given set of river-laid sands will have the steep slope on the same side, whereas in beds laid down under the action of tidal currents the steep slope will face in opposite directions with about equal frequency. The variable direction of the steep slope of asymmetric ripple-mark may thus be depended on to distinguish marine from river channel deposits.

Cross-bedding may be considered in connection with ripple-mark, because it probably represents in many instances one phase of a phenomenon called sand waves, which are nothing more than current-made ripple-mark of mammoth proportions (figure 10). Sand waves appear to be formed instead of ripple-mark when the current is overloaded with sediment. The crests are often 15 to 35 feet apart and rise from 2 to 3 feet above the troughs. They are formed on the beds of most streams which are heavily laden with sediment and along most coastlines which are subject to the action of powerful tidal currents. A set of beds which have been laid down in a zone characterized by sand-wave formation may not preserve the outlines of any single set of sand waves, but the steep forest beds which are formed as these waves travel with the current will be preserved as the familiar cross-bedding so common in many coarse sandstones. Cross-bedding is thus characteristic of both river and tidal current-laid beds. The direction of the inclined beds in the river deposits should, however, possess a degree of uniformity not shared by those which have been produced in marine deposits under the influence of a current

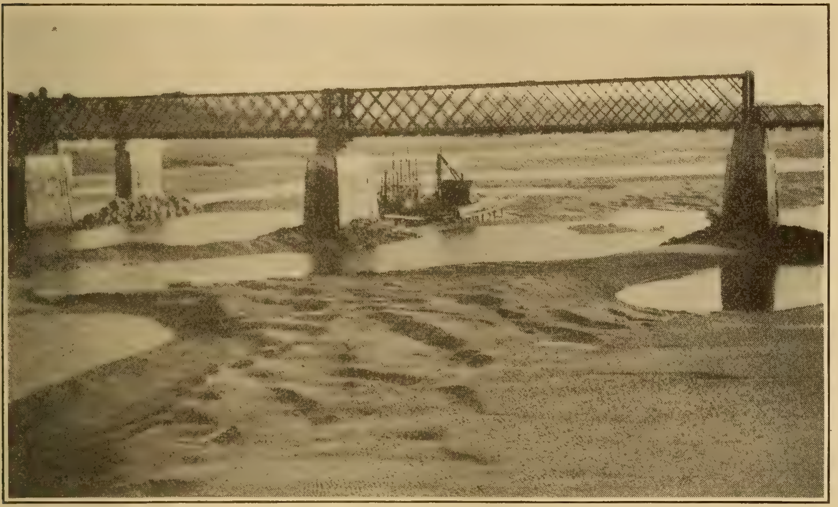

FIGURE 10.—*"Sand Waves," or mammoth Ripple-mark, Avon River, Nova Scotia*

which daily reverses its direction. The variable direction of the cross-bedding in marine clastics should serve to distinguish them from continental river-laid beds. If associated with ripple-mark they are easily distinguished from wind-blown or dune deposits, which also show great variability in the direction of their inclined beds. Wind ripple-mark is characterized by relatively low and water-current ripple-mark by relatively high crests (figure 7, *a-b*).

SUMMARY

In summarizing the preceding discussion of the criteria of marine clastics the significant facts which have been considered fall into three groups: 1. The distinctly different behavior of fine sediments in marine and in fresh waters. 2. The characteristic markings and texture of fine saline sediments developed during sedimentation and by desiccation. 3. The distinguishing features of marine and continental ripple-mark. Under the first head it has been shown that the extremely slow rate of deposition which characterizes fresh water as compared with marine sedimentation, when very fine sediments are involved, results in marine clastics showing more sharply defined boundaries between different types of sediment than continental or fresh-water clastics. The rate of deposition differs so greatly in the two classes of deposits that the order of superposition of adjacent coarse and fine beds may in some cases be in marine beds the reverse of that developed in fresh-water beds.

Deposition of finely divided sediments develops under conditions of rapid sedimentation pit and mound structures on the upper surface of the strata, which may sometimes be as serviceable in discriminating marine beds as rain-print impressions are in recognizing subaerial deposits.

Desiccated fresh-water mud may, under favorable conditions, be distinguished from desiccated saline mud by texture and by the character of the mud-cracks. Vesicular texture frequently develops in drying saline mud which is unknown in dried fresh-water mud. The mud-crack polygons in saline mud remain flat or curved down at the margins. In fresh-water mud the polygons curve upward, provided the tenacity of the mud is not sufficient to counteract this tendency.

Fossil ripple-mark should afford valuable aid in discriminating marine deposits. In marine sandstones the current type of ripple-mark will greatly predominate over the oscillation or wave type, while in lacustrine deposits the reverse will be the case. The current ripple-mark of marine deposits may be distinguished from that of river deposits by the variable current direction indicated by the former and the uniform current direction characteristic of the latter.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 28, PP. 917-924 DECEMBER 19, 1917

CHARACTERISTICS OF CONTINENTAL CLASTICS AND CHEMICAL DEPOSITS[1]

BY ELIOT BLACKWELDER

(Presented before the Society December 29, 1916)

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INTRODUCTION

Broadly considered, the continental sediments are all those which have been deposited elsewhere than in the sea. By this definition we must include among them not only the deposits made by rivers and other agencies working on the land, but also the sediments laid down in lakes and marshes. Between marine and continental types there is, of course, no sharp line of demarkation, but a transition zone occupied by the deposits made in estuaries, tidal lagoons, and sounds, on beaches, deltas, etcetera.

It would be gratifying if we could establish a few simple rules for distinguishing between marine and continental deposits; but with certain exceptions this is impracticable. There are but few satisfactory criteria of general application for separating continental from marine sediments.

In the past reliance has often been placed on the fossils; but in the continental sediments fossils are generally wanting, and not uncommonly

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[1] The fourth of a series of papers composing a "Symposium on the Interpretation of Sedimentary Rocks." This brevity of treatment is due to the fact that the time for presentation was limited to ten minutes.

Manuscript received by the Secretary of the Society March 24, 1917.

they are rare even in the marine deposits. It is no unusual experience for the geologist to chance on a formation, 5,000 or more feet thick, that is devoid of fossils; or if fossils are found they may not be indigenous, but imported, like the battered logs in the Triassic red beds of Arizona; or they may owe their presence to temporary invasions of the sea, like the marine limestones in the Pennsylvania coal measures. It is true that certain types of sediments, such as peat and saline beds, are made only on land, whereas such deposits as greensand and coral limestone are confined to the ocean; but these are not the most common deposits represented in our sedimentary rocks. Certain varieties of current-marks and cross-bedding may be limited to continental deposits. Sun-cracks are absent from marine deposits except the extreme littoral and are rare even there.

After all these general criteria for distinguishing marine and continental sediments have been taken into account, however, it must not be forgotten that most of them occur but locally, and that in many deposits all of them are lacking. It is hardly stretching the truth to say that most unfossiliferous strata require a critical analysis of various characteristics before they yield a satisfactory answer to the question of their origin.

In the modern ocean more than one-third of the deposits (areally) are non-clastic and nearly half are comprised in the unique abysmal red clay; on the continents, however, more than 95 per cent are clastic. The reasons for this contrast are too obvious to demand further mention.

Among the clastic deposits of the continents there is a wide range of variation within which nearly all possible intergradations may be found. On the whole there is far more difference between extreme types of continental clastics, such as till on the one hand and dune sand on the other, than between such a continental deposit as lake marl and such a marine sediment as calcareous mud. It is partly for this reason that no one criterion serves to distinguish the two general classes from each other.

Determining Factors

To bring order out of this seeming chaos and to present briefly the leading characteristics of the continental sediments, it is necessary to analyze and classify the sediments into distinctive kinds. We may first consider the factors which control the formation of these individual kinds The four principal factors seem to be:

(*a*) the lithology of the parent rocks,
(*b*) the processes of weathering at the source,
(*c*) the processes of transport and deposit,
(*d*) the conditions at the place of deposition.

Although of foremost importance locally in such deposits as landslides, the nature of the parent rock is but a minor factor in influencing the great bulk of continental sediments. The voluminous river deposits of diastrophic basins and deltas are generally derived from so large a variety of rocks that the materials are averaged. Nevertheless, lithology at the source becomes a factor of large consequence even in the basins of some large rivers, such as the Hwang-ho of China and our own Missouri, which on flowing through hundreds of miles of almost continuous loess deposits become charged with that material to the exclusion of most others.

The processes of weathering at the point of origin of the debris determines in large measure the kinds of minerals from among which the active agencies, such as streams, wind, and glaciers, may select material for their ultimate deposits. If solution and chemical decay are dominant, ferruginous sandy clays of rather simple mineral composition will normally result; but if physical disintegration prevails, then arkoses, wackes. and complex silts are likely to be formed.

The processes of transportation and deposition determine very largely the structure, topography, and texture of the deposit, as well as the shapes of the individual particles. They also assort and segregate the material into sediments of unlike mineral composition. Many continental clastics, such as moraine-stuff, dune sand, and loess, may be said to owe their most distinctive attributes to these transportive processes. Others are influenced less strongly, and some, like gypsum or peat, very little.

The conditions at the point of final deposition, being the last to affect the sediment, often exert the dominant influence in determining its character. A familiar example is furnished by the deoxidation of the ferric material derived from the bright red soils of the equatorial rain-belt, whereby, under the moist jungle of the river flats, it is converted into a dark gray or black mud.

On reviewing the four factors just mentioned, we find that the last three are controlled in large measure by the climate and subordinately by the topography. The topography exerts an important influence on the thickness, the situation, and the area of deposit, and frequently on its texture. But it is climate that not only shares these influences, but controls most of the other characteristics of a sedimentary deposit, for climate is the chief factor in determining the processes that shall be at work on the surface, their mutual relative values, and hence the composite result. To many students of the subject, therefore, a classification of the continental sediments based not on processes, but on the more fundamental factor of climate, modified by topography, seems the most serviceable. I have adopted that plan for this occasion.

Climatic Types of Sediments

CLASSIFICATION

It will serve present purposes to divide all continental sediments into three groups:

(*a*) the pure or extreme types,
(*b*) the mixed types,
(*c*) the intermediate types.

PURE OR EXTREME TYPES

Sub-Arctic type.—In the first group we may distinguish the sub-Arctic, the humid tropical, and the desert types; in the second (or mixed) group deposits made under alternating wet and dry seasons, and also sediments that have been transferred from one climate to another, and in the last (or intermediate) group various intergradations between the primary types. For the sake of brevity, I omit the purely glacial Arctic type.

In the sub-Arctic regions the deposits made by rivers in their deltas and structural depressions are probably the most important in quantity. The ideal conditions are found in the valleys of the Yukon, Mackenzie, Lena, Yenesei, and many others. In these fluviatile sediments the minerals are but little decayed, because frost action is the chief process of weathering at the source. They are also associated with abundant carbonized vegetable matter, because vegetation is not only plentiful, but under the prevailing conditions decays slowly and leaves a copious residue. The result is the deposition of complex anhydrous silts, undecayed wackes, and gravels, in which some shade of gray or black is the characteristic color, for a saturated and often a frozen soil charged with decaying organic matter leaves little opportunity for oxidation and the development of the brighter colors. For the same reason sun-cracks rarely develop. Carbonized wood is not uncommon in such deposits, and leaves may locally be abundant; but vertebrates are rare and mollusks much more so.

The associated minor deposits, any one of which may locally become predominant, are peat, glacial till, lacustrine silts, soil flows, and talus. The whole series is characterized by the abundance of undecayed silicate minerals, sombre colors, by absence of saline deposits, and by absence or scarcity of other formations that are distinctive of the hot climates.

Humid, tropical type.—In partial contrast to the sub-Arctic is the humid, tropical type, best exemplified by deposits made on the windward side of tropical islands and coasts. Obviously, it is far less extensive in area, and therefore in quantitative importance, than the sub-Arctic series, doubtless including less than 5 per cent of the continental deposits. Here again such sediments as are made are chiefly fluviatile. Owing to the effectiveness of solution and chemical decay over the hills from which the streams derive their sediment, the minerals of the eventual deposits on the lowlands are greatly simplified. The ferruginous clays, rich in hydroxides and hydrous silicates, overwhelmingly predominate. Being deposited on the moist bottom lands, these sediments become richly charged with organic matter and are generally saturated with water. Therefore, in spite of the fact that they are usually derived from red lateritic soils, they tend to become partly deoxidized and either decolorized or blackened by the excess of organic matter. As in the sub-Arctic family of sediments, peaty deposits and soil flows are among their associates; but both of these differ in actual composition from the peaty and solifluctional deposits of high latitudes. They also resemble the sub-Arctic group in being devoid of saline and eolian deposits. Unlike that group, however, they of course never contain interbedded till sheets, and the minor deposits of mud and biochemical residues made in lakes and marshes are probably quite different, although as yet but poorly known in detail.

Desert type.—The desert family of sediments, forming the third corner of our triangle, is very distinct from the others. Deserts are said to cover 20 per cent of the land surface, and although over a large part of that area the rock is bare rather than deeply covered with sediments, it is nevertheless almost certain that the quantity of desert deposits is much greater than that of the humid, tropical type. Even in deserts the deposits made by streams, evanescent though they are, probably exceed those of all other agencies, and this in spite of the fact that the wind is doubtless the most important erosive agency there at work, for in contrast with the streams the wind exports most of its product. The transient streams of the desert make two rather distinct types of deposits, which may be called (as suggested by Tolman) the "bajada" and the "playa" types. The materials of the "bajada" or piedmont slope deposits are, as a rule, both poorly and variably stratified. The minerals are but little decayed and therefore consist largely of unaltered silicates. Although in this respect they resemble the sediments of the sub-Arctic group, they differ radically from the latter in being practically devoid of organic matter. Their colors are therefore generally pale, such tints as buff and light gray predominating. There is every textural variation among bajada deposits, from coarse boulders down to silts, and generally particles of many sizes are closely intermingled. This well known imperfection of assortment is due to the hasty but brief action of the desert thunder-storms. Often the transient stream is a river of mud, in which particles have but little freedom of movement.

The deposits made in the playas or temporary lakes are brought to them largely by the streams. They are fine of texture and evenly stratified, save where the delta structure appears. They are likely to be impregnated with crystals and interstratified with beds of chemically deposited salts. Like the bajada deposits with which they intergrade, they are usually pale in color. This is perhaps the most favorable of all situations for the development of shrinkage cracks and for their preservation. With the playa, and even with the bajada, type of desert deposits we find associated a variable amount of dune sands—the purest, cleanest, and usually the best rounded of all sands. In some regions they are almost the sole deposits of the desert.

MIXED TYPES

Having considered the three extreme climatic types, we may now review the more distinctive mixed varieties.

In those lands which are visited in the course of the year by two distinct climates there is a corresponding effect on the sediments deposited. These conditions are found best developed in regions affected by the monsoons and the belt a few degrees wide along the equator. The alluvium of the Indo-Gangetic plain affords perhaps the classic, although a not altogether typical, example. The deposits of such regions are necessarily hybrids between those of the desert on one side and the humid tropical region on the other. The thorough chemical decay of rocks in well drained hills subject to a pronounced rainy season yields ferruginous clays, normally of bright red color. These are carried down and deposited on deltas and floodplains which are hot and parched for several months during the year. On such plains a rank growth of vegetation is not favored, and the sun burns out any residue of decayed organic matter that may develop in the rainy season. During the long droughts, when the water table sinks several feet, or even meters, below the surface, the most recently deposited layer of silt becomes thoroughly dry and aerated. The sediments, therefore, tend to remain oxidized, and even to become dehydrated. Hence red and brown colors are the rule. Deposits of this kind are characterized by abundant sun-cracks, being perhaps excelled in this respect only by the playa deposits of the desert. Among fossils the footprints of land vertebrates may be common in deposits of post-Paleozoic age. Fish remains appear in extraordinary numbers, but only in certain rare layers—probably an indication that overflow lakes from the rivers of the wet season had subsequently shrunk until the fishes were left to perish in the mud of the last remaining pools. The associates of the river sediments are distinctive. Peat is scarce, but on the other hand saline deposits are not typical of either monsoon or doldrum regions.

Where long rivers carry sediments from one climatic zone into another, we have another variety of the mixed climatic type. There is no better example of this than the Nile, although the Mississippi and many other streams of great length have much in common with it. In some respects the sediments of these rivers are much like those produced by annual changes from wet to dry climate in the same area; but in others new factors are introduced and the results vary correspondingly.

INTERMEDIATE TYPES

Thus far we have, of course, dealt only with the more distinct climatic types, neglecting the fact that they all intergrade with one another through an almost infinite variety of intermediate stages. A few are so distinctive as to merit special mention, even in so brief a review as this. Because of vast areas affected, I select two of the most important, namely, the *temperate subarid* and the *temperate subhumid* types of deposit.

In regions like the Great Plains of the United States and the steppes of southern Russia and Siberia, where the rainfall is occasional rather than seasonal, and yet is sufficient for the development of a grassy turf, though not for the growth of a forest cover, the streams and the wind vie with each other for mastery in the formation of the sediments. The river deposits usually present an averaging of the characteristics of the sub-Arctic, the moist tropical and the desert types, being but imperfectly either decayed, hydrated, or oxidized, and being associated with a small amount of partly decayed vegetable matter. They therefore contain many unaltered silicates, such as feldspar and mica, along with some kaolin and iron oxides. Their characteristic colors are buff and brown, with black very subordinate. There is but little peat, and on the other hand rarely deposits of salts. Sun-cracks are abundantly developed, but the conditions for their preservation are not quite so good as in the arid and seasonally arid regions. The most characteristic sediment of this climatic type is undoubtedly the loess. Most students of the subject now regard the loess as being the dust carried from more arid regions out over the adjacent prairie or grassy lands, where it is entrapped by the turf and held in constantly increasing thickness. This eolian loess, in turn, is subject to reworking by the streams, which then impress on it their appropriate modifications and thereby convert it into "river loess." True eolian loess consists largely of grains and splinters of quartz, undecayed silicates, and even carbonates. The proportions of kaolin and iron oxides are relatively low. Its obscure stratification, its pale buff color, its dry-land fossils, and its ability to stand in vertical cliffs are well known. A genetic relation to glaciation has been urged by certain geologists for some of our loess deposits, but this has been definitely established in very few cases. Some of the greatest loess deposits seem to have no relation to glaciation.

An increase in the occasional rainfall of the temperate regions to forty or more inches a year produces in the sediments changes important enough to deserve recognition. In these subhumid temperate regions the rivers, fresh lakes, and marshes are the chief agencies of sedimentation. The alluvium of the Tennessee River and of many other short rivers in the temperate zone would serve as examples. We must bear in mind that nearly all of the streams in regions of this kind have reached grade (profile of equilibrium), and hence make deposits of noteworthy thickness only at their mouths or where they cross structural depressions, such as grabens and downwarps. Both gravels on the one hand and ferric clays on the other are deficient. Sandy silts and clay silts predominate. Even if derived from red soils, after deposition they normally turn gray or grayish brown because of the generous amount of residual organic matter present. Black peaty deposits are rather common, but the formation of typical loess is not favored. Neither till nor saline deposits can be made under such conditions. Like the deposits of the tropical moist belt, these sediments have generally lost by leaching most of the more soluble constituents, such as the alkalis, lime, and magnesia, and yet they do not contain a high percentage of the aluminous hydroxides which are distinctive of the humid tropics.

Limitations of space prevent me from discussing even casually the many other interesting mixed and intermediate types, such as the hybrids between the sub-Arctic and the desert (western Siberia), the Alpine sub-Arctic with the tropical (central Andes, Ruwenzori, etcetera), or with the type of alternating climates (sub-Himalayan). Most of these still await critical study, although many of their characteristics might safely be predicted in advance by reasoning deductively from known principles.

Need of Exact Data

In closing, I wish to express the opinion that the present study of sedimentation rests too largely on such deductive reasoning from physiography and climate and too little on the rigorous inductive consideration of minute field observations and laboratory experiments. The field geologist can render very important service by giving as close attention as his time may permit to all modern sedimentary deposits which he finds and to their mode and conditions of origin. By collecting samples of such sediments with adequate field notes and afterward submitting them to specialists for study, he will supply the material for much valuable laboratory research and will thus help to accelerate the genuine advance of our knowledge of the sediments.

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SIGNIFICANCE OF SORTING IN SEDIMENTARY ROCKS[1]

BY EUGENE WESLEY SHAW

(Presented before the Society December 29, 1916)

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DOMINANT CONSIDERATIONS AND THE QUESTION RAISED

The facts that the grains composing most sedimentary rocks show more or less sorting, that this sorting is not uniform, either in degree or kind, and that the rocks are known to have been laid down by various agents, naturally leads to the question: To what extent may it be possible to determine, from the mechanical constitution of a layer of sedimentary rock, what conditions and processes affected its deposition? The term sedimentary rock is here used in preference to clastic rock, for not only do most deposits which were once sediments show some sorting, but the grains composing many of the so-called chemical deposits, particularly the limestones, seem to have been transported and sized to a greater extent than generally realized. One is deeply impressed with this fact, particularly when observing the sea bottom in diving apparatus. The lime-de-

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[1] The fifth of a series of papers composing a "Symposium on the Interpretation of Sedimentary Rocks."

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positing waters around Florida and Yucatan, for example, sweep the deposits about over the bottom, and are commonly so loaded with sediment in suspension that one exclaims here is transportation on such a scale as to make the Mississippi's annual 470 million tons seem small in comparison.

THE FACTORS AFFECTING SORTING

A brief consideration of the probable causes of the sorted or sized nature of an unmodified sedimentary deposit leads to the inference that the causes are very complex and that the result depends on such factors as the following:

1. Character, particularly granularity and degree of sorting, of parent materials from which the grains composing the deposit came. The erosion product of an even-grained rock is likely to be uniform in grain, whatever the nature of the transporting and depositing agent. If a sea cuts into a hill having a layer of small pebbles and a layer of larger ones, it may build a beach in which pebbles of two sizes preponderate.
2. Method and ease with which the grains yield to processes of cracking, attrition, and solution, and the vigor of these processes.
3. The nature of the current, including its velocity, variations in velocity, variations in direction, and length of time it acts.
4. The absolute and relative amount of sediment delivered to the depositing agent per unit of time.
5. The area over which this agent operates—its average depth and variations in depth.
6. The presence or absence of eddies or departures from uniformity in velocity of threads of depositing agent.
7. Specific gravities of depositing agent and grains of sediment.
8. The viscosity of the depositing agent.
9. Shapes of grains, particularly if grains of one size tend to have one shape and those of another a different shape.

Molecular attractions play an appreciable part in very fine-grained material, particularly in the sorting of sticky clay flakes. A current may carry away all material below a certain size, and the relict deposit will thus have a peculiar nature.

Mechanical analyses of sediments of known origin seem to confirm the inference that the causes of sorting are very complex, for they seem to show infinite variety, even within a single class, such as river deposits. An analysis of one river deposit may be more like that of an ocean deposit than that of another river deposit. A well washed and sized beach gravel or sand may or may not have its interstices filled or partly filled with smaller grains. Apparently most mechanical analyses barely furnish bases for guesses as to genesis, and often one guess is as good as another.

Note on previous Workers

However, as Atterberg,[2] Mohr,[3] Thoulet,[4] Udden,[5] Gilbert,[6] Goldman,[7] and others have pointed out, some analyses have significance, those of dune sands in particular being commonly recognizable by the average size of grain and high degree of sorting, though beach sand is also well sorted.

Methods of making Analyses

The principal methods which have been used in mechanical analysis are the following: Hilgard, the eminent authority on soils, used both screens and elutriating apparatus very extensively, and his separates ranged in size from ¼ mm. to 64 mm., the grains of each separate being twice the size of those in the next finer separate.

Atterberg's separates range from .001 mm. to 5 mm. His ratio was not fixed, but is approximately 2.

Mohr makes separates ranging from 10 mm. down to .0005 mm. by allowing particles to settle through water, his finest particles requiring a week to settle 20 centimeters.

Thoulet uses a more irregular series of ratios ranging from 2 to 6, and his separates range from .04 mm. to 15 mm.

The U. S. Bureau of Soils makes separates ranging from .005 mm. to 2 mm. by the use of screens and centrifuges, and the ratio between sizes ranges from 2 to 10.

Methods of studying Analyses

Diagrammatic representation is so advantageous as to be practically requisite in the study of mechanical analyses. Two forms, which may be designated the integral and the cumulative, seem to be most expressive. In the first, the amounts of grains of each size are represented by columns having heights corresponding to the percentages as given in the analysis, the coarsest being represented on the left and the others following in regular order. The second differs in that each column represents the grains of one size plus all of larger size. If each column in the integral diagram represents particles averaging two or a multiple of two times the diameter of the next on the left, the highest column, conveniently designated as the maximum, is likely to be centrally located, and the height of the other columns generally decreases more or less regularly from this central column outward. If the centers of the tops of the columns be joined by straight lines, these lines together have a form resembling more or less closely a curve of probability, and to this curve they obviously have a logical relation. Analyses that give the highest maximum column are, of course, the best sorted. It should be noted that mechanical analyses are not so precise as they appear to be, and great precision is not only impracticable, but perhaps not greatly to be desired.

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[2] A. Atterberg: Die rationelle Klassifikation der Sand u. Kiese. Chem. Zeitung, xxix, no. 15, 1905, pp. 195-198. Also his "Über die Korngrösse der Dünensande," same journal and volume, no. 80, p. 1074.

[3] E. C. J. Mohr: Ergebnisse mechanischer Analysen tropischer Böden. Bull. de Départ. de l'Agric. aux Indes néerlandaises, no. 47, Buitenzorg, 1911.

[4] J. Thoulet: Étude bathylithologique des côtes du Golfe du Lion. Annales de l'Inst. Oceanogr., Monaco, vol. iv, 1912, fasc. 6.

[5] J. A. Udden: Mechanical composition of clastic sediments. Bull. Geol. Soc. Am., vol. 25, no. 4, December, 1914, pp. 655-744.

[6] G. K. Gilbert: The transportation of débris by running water. U. S. Geol. Survey Professional Paper 86, 1914.

[7] M. I. Goldman: Petrographic evidence on the origin of the Catahoula sandstone of Texas. Am. Jour. Sci., 4th ser., vol. xxxix, March, 1915, pp. 261-287.

SIZES OF GRAINS IN SEPARATES

Mechanical analyses have been made by various men and organizations, and there are almost as many systems of sizing as there were men and organizations. Still, few have used the actual number of particles of various sizes, and no one has put the separation on a purely arithmetical basis. For example, no one has classified the particles making up a sediment, each of which differs from the next size by a millimeter. There seems to be rather general agreement in making the size of grains in each separate about twice the diameter of the next coarser, though very often a separate is made in which the size of the particle is ten times the size of that of the next smaller. Very few have used a single ratio consistently throughout. Udden, one of these exceptions, makes the size of grains in each separate twice the diameter of the next smaller, or, rather, in each separate the particles of maximum size are twice the diameter of those of minimum size. No one seems to have made separates on the basis of cubical content or weight of the individual particles, and no one has used consistently the cross-section areas of the particles.

SIGNIFICANT FEATURES OF DIAGRAMS

If a few hundred analyses of sediments of various origins selected at random, or, better, with the idea of using the most representative ones, be recast to the single-ratio basis, and plotted in integral diagrams, and if these diagrams be critically examined for diagnostic features, several such features may be picked out, some of which have already been discussed in print. First may be mentioned the comparatively high degree of sorting shown by beach and wind deposits, including both dune sand and dust. Second, as might have been expected, glacial till diagrams are low and broad, showing little sorting. Yet, surprising at it may seem, few of them show no sorting at all. The few analyses of breccia available show less sorting than the average glacial till, and yet, if the breccia has shifted a little it may show signs of the peculiar obscure sorting of talus. Whether the sorting of till is that of an unsorted mixture of many kinds of residuum, or is of a different nature, has not been determined. Some water deposits, particularly marine offshore deposits, show two maxima, one of which is due to sorting and the other to the shells of some very abundant organism. Third, Udden's inference that in eolian sands the portion next in amount to the maximum is coarser in grain, and that this is somewhat characteristic of eolian deposits, seems to hold in a general way. However, although in diagrams of dune sands the column next to the tallest is likely to be on the left or coarse side, in dusts, particularly loess, it seems more likely to be on the right. Fourth, Udden's "Index of sorting for aqueous sediments produced by drifting and silting" is 2½ to 1, and for "eolian sediments produced by analogous modes of blowing and dusting" is near 4½ to 1. This means that, on the whole, eolian sediments of the kinds mentioned are much better assorted than aqueous, and the ratios correspond to the ratios in heights between any column in the integral diagram based on the ratio 2 and one next to it.

POSSIBILITY OF OTHER SIGNIFICANT FEATURES BEING FOUND

Perhaps other features, such as ratios of column heights, or of proportionate amounts finer and coarser than the maximum, or some more obscure but persistent character, may be brought out by further study, for the diagrams of individual analyses are extremely variable. A part of this variation is really not inherent in the sediment, largely because no two analysts would agree exactly as to the composition of a sediment, and because some samples analyzed have been taken from single thin layers and others from an inch or more of deposit which commonly involves several layers or conditions of deposition.

Fundamental Cause of Sorting

If one attempts to evaluate deductively the factors affecting nature and degree of sorting, and particularly to classify them according to whether, on the whole, they probably favor or retard sorting, he may arrive at the conclusion that the fundamental cause of most sorting is the friction which tends to retard the relative movement of a solid body through a fluid medium. In other words, we may regard the causes of sorting as relatively simple and the retarding factors numerous and complex. The friction increases as the square root of the diameter of the grains—shape, specific gravity, and other factors being equal. If a handful of unsorted, well rounded coarse sand and fine gravel be dropped into a deep and very slowly moving stream of water of uniform velocity and cross-section, the coarsest particles will reach the bottom in the shortest distance, those of half the diameter of the coarsest in four times the distance, those of one-fourth the diameter in sixteen times the distance, and so on. If some very fine particles had been included, they would, on account of this geometric ratio, require an almost infinite distance to reach the bottom, and thus remain in suspension almost indefinitely.

If, after most of the grains have reached bottom, the channel is tilted a little, so as to give the current sufficient velocity to move the particles along the bottom, the same law of friction again becomes operative, though now the water is moving faster than the grains.

On account of these considerations it seems highly desirable to make the sizes separated in mechanical analyses bear a fixed ratio to each other, and this ratio should be 4, 2, the square root of 2, or the fourth root of 2. If an arithmetic progression is used, or a variable ratio, the result is a distorted picture of the sediment, and one which can not be readily interpreted in the light of the fundamental principle of sorting.

Attempts to analyze the factors modifying the effect of sorting processes raise repeatedly the query: Even though the factors are numerous and complex and the analyses show unlimited variety, may it not be that each factor, or at least some of them individually or by groups, have some obscure and heretofore unnoticed effect on mechanical composition which can be discovered by careful study and comparison?

Perhaps, on account of the fact that mechanical analyses seem to throw little light on the genesis of a sediment, only a few hundred of them are available. Among these, some kinds of deposits, as, for example, dune sand, are much more abundantly represented than others. A few weeks' study of the available analyses, including their representation in various diagrammatic forms, has failed to bring to light many new and significant features of individual analyses worthy of mention. It, however, does not prove that such features are not present and will not be gradually brought to light.

"MONOGRAMS" OF VARIOUS KINDS OF DEPOSITS

However, groups of analyses, each belonging to a single class of deposits, when taken together, show much greater promise of diagnostic features. If 10 analyses of dune sand taken at random be plotted in the form of cumulative logarithmic diagrams, and these diagrams be superposed, a figure is obtained which at present seems to be characteristic of dune sand. Other groups of 10 dune sands taken at random are found to give figures of closely similar form. The writer has fallen into the habit of calling these figures "monograms," for each consists of lines crossing each other in various ways, and the form of the network, as well as of the individual lines, seems to have significance.

The similar plotting of groups of 10 analyses of other kinds of sediments lends strong support to the notion that monograms prepared in this way may in some cases be diagnostic of the kind of sediment. If 10, 20, or 50 analyses of the Dakota sandstone were made, it seems very doubtful if, in the present state of knowledge, any single analysis would of itself throw much light on the conditions of the deposition of the sandstone; but if all were plotted one on another, the resultant compound figure might throw a great deal of light on the genesis of the deposit.

The writer would like to emphasize an inference already made by other investigators, but not yet generally appreciated, this inference being that most limestones were once clastic, and the particles were sorted before final deposition. Thus limestones which are not too extensively recrystallized can be studied as though they were sandstone or conglomerate.

CONCLUSION

Although, as is shown by both theory and observation, many factors affect the sorting of each kind of sediment, the principal underlying cause of sorting is the difference in the friction involved in the movement of particles of different sizes through a fluid. With occasional exceptions, it is not yet possible to infer correctly the origin of a sediment from a mechanical analysis, yet it seems probable that by further study more and more significance will be found in such analyses; in other words, that a sufficient number of observations will bring to light diagnostic features by which certain kinds of sediment can be recognized and the identification of others narrowed to a few possibilities. At present the most promising line of attack is the comparative study of groups of analyses, each group of a single deposit or a single kind of sediment.

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CHEMICAL AND ORGANIC DEPOSITS OF THE SEA[1]

BY THOMAS WAYLAND VAUGHAN

(*Presented before the Society December 29, 1916*)

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INTRODUCTION

As the discussion of this subject is necessarily brief, no attempt will be made to review the classification of organic and chemical deposits advanced by Murray and Renard in the *Challenger* reports, and I will immediately pass to the consideration of some of the results obtained from researches made during the past ten years. My remarks will be for the most part confined to the discussion of deposits formed in water less than 100 fathoms deep, because recent investigation has been chiefly directed to these and because the geologist usually encounters relatively shallow-water sediments in his field-work. However, in places accumulations of pelagic foraminifera, of radiolarian earths, and of certain particular kinds of manganese nodules above present sealevel indicate that some ancient deep-sea deposits have been elevated from several thousand feet below the surface of the ocean and now form parts of dry-land areas; but the areas occupied by such deposits are relatively small in comparison with the enormous extent of sediments of shallow-water origin.

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[1] This is the sixth of a series of papers composing a "Symposium on the Interpretation of Sedimentary Rocks."

Manuscript received by the Secretary of the Society April 24, 1917.

AUTHOR'S NOTE.—The short paper herewith presented is to some extent an abstract of a larger paper by myself in collaboration with J. A. Cushman, M. I. Goldman, M. A. Howe, and others, entitled "Some shoal-water bottom samples from Murray Island, Australia, and comparisons of them with samples from Florida and the Bahamas," Carnegie Institution of Washington Pub. 213, 1917, pp. 235-297. The accompanying tables are taken from the larger paper, but the illustrations on plates 47 and 48 are published for the first time. It is published by permission of the President of the Carnegie Institution of Washington and of the Director of the U. S. Geological Survey.

In order to make an application of the results procured from a study of modern sediments to the interpretation of the conditions under which the older were formed, samples must be collected and studied, and all obtainable information regarding the conditions under which they were deposited should be gathered. This information should include the relations of the deposit to land areas, the configuration of the sea-bottom, the velocity and direction of winds and currents, and the depth, temperature, and salinity of the water. Air temperature, rainfall, and surface run-off and sediment from adjacent land areas, where there are such, should also be known; and it is desirable to know the chemical composition of the water discharged into the sea and that of the rocks over which or through which it passes.

Each sample should be divided into four parts, unless the quantity of the material is large. One part should be preserved intact, the second used for a chemical analysis, the third for a mechanical analysis and petrologic study, and the fourth for a detailed list of the important organisms entering into its composition.

Although complete analyses of selected samples are needed, the analyses usually are only partial, because of the impracticability of having an indefinite amount of chemical work performed. SiO_2, Fe_2O_3, Al_2O_3, CaO, MgO, P_2O_5, and SO_3 are determined in as many samples as practicable, while CaO and MgO and insoluble residue after ignition are determined in a larger number. The ratio of MgO to CaO (or of the hypothetical combinations $MgCO_3$ to $CaCO_3$) is highly important, as will later be made clear.

Mechanical analyses have been sufficiently discussed by Mr. Shaw in the immediately preceding paper.

Chemical Deposits

As the chemical deposit of greatest geologic importance in the shoal waters of the ocean is calcium carbonate, attention will be confined to it. No argument is needed to show that to understand the relative saturation of the ocean with reference to $CaCO_3$ is of prime importance. Fortunately the subject has recently been attacked by a number of investigators.

As a part of a discussion of the formation of atoll rims, I summarized the results obtained up to 1914 as follows:[2]

> "(1) All the bays, sounds, and lagoons within the Florida reef and key region are filling with sediment; (2) Drew's investigations of dentrifying bacteria show that chemical precipitation of calcium carbonate is taking place in the lagoons; (3) the chemical examination by R. B. Dole of samples of sea

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[2] Wash. Acad. Sci. Jour., vol. 4, Jan. 19, 1914, pp. 27-28.

water flowing into and out of the Tortugas lagoon show that although both carbonate and bicarbonate radicles are in solution, uncombined carbon dioxide is not present, and that the water possesses no capacity for further solution of calcium carbonate by virtue of its content of free carbon dioxide; (4) the determinations by Dole of the salinity of the water within the Tortugas lagoon and at the southern end of Biscayne Bay show a higher concentration than that in the open sea-water on the outside, indicating that concentration by evaporation is taking place. As the results of these lines of inquiry are so positive, the formation of lagoons by submarine solution may be definitely eliminated from consideration."

Johnston and Williamson have recently paid particular attention to the solubility-product constant $[Ca^{++}]$ $[CO_3^{=}]$, the concentration of H_2CO_3, the effect of temperature on H_2CO_3 concentration, and the relation of the solubility-product constant to rise in temperature, and say:

> "We believe therefore that the surface layers of the ocean, except in the polar regions and within currents of cold water—in other words, the warmer portions of the ocean—are substantially saturated with $CaCO_3$; but the truth of this belief can not be regarded as established until trustworthy determinations of the several quantities concerned have been made."[3]

The latest contribution to the subject is by R. C. Wells in an article entitled "The solubility of calcite in sea-water in contact with the atmosphere and its variation with temperature."[4] His experiments were conducted with water from Fowey Rocks Light, Florida, collected between July 19 to 25, 1915. He says:

> "In other words, sea-water appears to contain so much carbonate that in contact with the atmosphere at 1° C. it neither has nor acquires an appreciable solvent action on calcite. At higher temperatures it undergoes a slow diminution in its content of carbonates on being agitated in contact with outdoor air."

The evidence appears to me conclusive that ocean water, except at great depths and probably on the surface in polar regions, is saturated with $CaCO_3$. If this conclusion is granted, it is obvious that any agency that increases the $CaCO_3$ concentration or that diminishes the capacity of the water to hold $CaCO_3$ in solution will produce precipitation.

Are there precipitating agencies? There are, and they are both inorganic and organic. Of the inorganic agents there are three, as follows: (1) Increased concentration due to evaporation. (2) Loss of CO_2 into the atmosphere where the CO_2 content of the atmosphere is below the amount necessary for equilibrium with that of the water. The loss of CO_2 under such conditions will be hastened by surface agitation of the water. (3) Loss of CO_3 by increase in temperature. Of the organic agents, bacteria appear to be the most important. As the result of the investigations of Drew and of Kellerman on dentrifying bacteria are now generally known, it is here only necessary to say that these organisms evolve ammonia which may take up CO_2 from bicarbonates or may react with calcium sulphate, producing an excess of $CaCO_3$, which consequently is precipitated. Any other ammonifying bacteria will produce the same result, and green plants by robbing the water of CO_2 may bring about precipitation.

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[3] Jour. Geol., vol. 24, Dec., 1916, p. 735.

[4] Carnegie Inst. Washington Pub. 213, 1917, pp. 316-318.

An evaluation of the work done by inorganic and organic agencies has not yet been made, and it is exceedingly difficult, if not actually impossible, to make it. For instance, off the west side of Andros Island, Bahamas, opposite South Bight, where the deposit is largely a chemical precipitate, the salinity of a spot sample of water was 38.86 parts per thousand, while that of the tongue of the ocean east of Andros Island was about 36.50 parts per thousand, and that of the water at Fowey Rocks, Florida, is about 36 parts per thousand. The increased concentration would necessarily cause precipitation. At the same locality there is surface agitation of the water; and as there is an enormous submarine flat, having a width east and west of 60 sea miles and a maximum depth of only about 18 feet below mean low-tide level, the temperature during the hotter months of the year would naturally be higher than in the open ocean. Therefore all three inorganic agencies are operative. At the same locality Drew found "160,000,000 dentrifying bacteria per 1 cubic centimeter,"[5] and thought the actual number probably greater. The problem is complex and needs further investigation.

Although the criteria for recognizing chemical precipitates in bottom samples have not yet been worked out in the desired detail, some of them may be mentioned. Among them are spherulites, separate aragonite needles, and aggregates of aragonite needles into the globular, ovoid, or ellipsoidal bodies known as oolite grains. Illustrations of these are given on plate 47, figures 1 to 7, and plate 48, figures 1 to 3 (see page 944).

For purposes of comparison, besides mounts of such objects as are shown on plates 47 and 48, those of us engaged in these studies have many preparations of artificial and natural precipitates. The paper by Messrs. Johnston, Merwin, and Williamson, entitled "The several forms of calcium carbonate,"[6] is of great value in this connection.

With reference to the chemical composition of deposits of the kind under consideration, it will be said that they are almost pure calcium carbonate. Excluding silica, the elevated oolites of Florida and the Bahamas contain over 99 per cent $CaCO_3$ and only traces of $MgCO_3$; in the oolitic muds, however, $MgCO_3$ usually ranges from about 2.7 to about 3 per cent, this larger percentage probably being due to the presence of alcyon arian epicules and of foraminiferal shells and other organic tests that contain $MgCO_3$. The oolites, both those elevated and those submarine, seem uniformly to contain a little $CaSO_4$, which, according to Messrs. Johnston, Merwin, and Williamson, is probably necessary for the formation of aragonite at ordinary sea temperatures.

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[5] Carnegie Inst. Washington Pub. No. 182, 1914, pp. 41-43.
[6] Am. Jour. Sci., vol. 41, 1916, pp. 473-512.

Chemical Analyses of Oolite and bottom Samples from Florida and the Bahamas

(By W. C. Wheeler)

	Oolite, Boca Grande Key, Florida.	Oolite, Everglades, Miami, Florida.	Oolite Sharp Point, Andros Island.	Bottom sample[7] (98), east side Marquesas Lagoon, Florida.	Bottom sample[8] (87), 1 mile west of west end of South Bight, Bahamas.
Chemical Analyses					
	p. ct.	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
SiO_2	0.03	[9]8.23	0.07	1.13	0.28
Al_2O_3	.18	.00	.00	.14	.03
Fe_2O_3	.22	.21	.13	.21 (total Fe)	.11 (total Fe)
MgO	Trace.	Trace.	Trace.	1.31	1.25
CaO	53.77	51.60	54.57	51.04	52.30
Na_2O	.90	.11	.14	.....	.....
K_2O	Trace.	Trace.	Trace.	.....	.....
H_2O	1.21	.17	1.72	2.03 (and organic)	3.16 (and organic)
CO_2	42.34	40.11	43.07	41.50	42.45
P_2O_5	Trace.	Trace.	Trace.	.....	.....
SO_3	.28	Trace.	.14	.....	.....
Cl	1.02	.08	.03	.....	.....
Soluble	.....	.....	.....	[10]2.21	.....
Total	99.95	100.51	99.87	99.57	99.58
Reduced analysis (hypothetical combination); H_2O, organic matter, and soluble salts rejected; silica not essential.					
SiO_2	0.03	8.19	0.07	1.18	0.29
$(Al, Fe)_2O_3$	.42	.21	.13	.37	.15
$MgCO_3$	Trace.	Trace.	Trace.	2.88	2.72
$CaCO_3$	99.05	91.60	99.56	95.57	96.84
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	.....	.....
$CaSO_4$	.50	Trace.	.24	.....	.....
Total	100.00	100.00	100.00	100.00	100.00

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[7] Samples washed and dried over H_2SO_4.

[8] Sample filtered, washed, and dried over H_2SO_4.

[9] Twenty-five per cent soluble SiO_2; the rest of the silica appears to be white sand.

[10] Saline salts not washed out by water in the preparation of the sample.

Conditions are most favorable for the precipitation of calcium carbonate and for the accumulation of the precipitated material, which at first is in a very finely divided state, where the temperature of the sea is high and where there are relatively shallow bodies of water that are protected from heavy seas and strong currents. On actual coral reefs there seems to be no chemically precipitated calcium carbonate, and there is but little of it along the channels through lagoons. The amount of material of such an origin in specific localities is graded in accordance with the character and strength of winds and local currents.[11]

ORGANIC DEPOSITS

In the investigation of organic deposits, after the mechanical analysis has been made, the separates are studied to determine the proportion of each of the ingredients composing each separate. In order to facilitate the recognition of the ingredients, a reference collection of coccolithophoridæ, diatoms, calcareous algæ, radiolaria, foraminifera, madreporarian and alcyonarian corals, echinoids, bryozoa, mollusks, crustacea, bones, etcetera, is necessary. The skeletons of the larger organisms are prepared for study as thin sections and mounted crushed fragments. The tables of the analyses of the skeletons of marine invertebrates and of calcareous algæ, recently prepared by F. W. Clarke and W. C. Wheeler, make possible estimating the proportion of the chemical constituents contributed by each group of organisms that takes part in the formation of the deposit. The following are estimates by Dr. M. I. Goldman of the averages for the composition of the marine invertebrates and calcareous algæ at Murray Island, Australia, using the Clarke and Wheeler tables as the basis of his estimates. Two tables of analyses, one of calcareous algæ and one of foraminifera, are here presented. It seems probable that Doctor Goldman's estimate of the $MgCO_3$ content of the *Corallinaceæ* is a little too high.

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[11] This subject is discussed in considerable detail in the larger paper referred to in the footnote on page 933.

Average Composition of the Skeletons of marine Invertebrates and of Calcareous Algæ, estimated for Murray Island, Australia

	$CaCO_3$.	$MgCO_3$.	$CaSO_4$.	$Ca_3P_2O_8$.
Corallinaceæ	80.00	19.00	1.00	......
Halimeda	99.00	.50	.50	......
Mean alga	89.50	9.75	.75	......
Madreporaria	99.30	.70	......	......
Alcyonaria	75.00	15.00	......	8.00
Mollusks	99.75	.25	......	......
Tinoporus	89.00	11.00	......	......
Amphistegina	95.20	4.80	......	......
Orbitolites	89.40	10.60	......	......
Polytrema	88.75	11.25	......	......
Approximate average foraminifera	89.50	10.50	......	......
Crustacea:				
(1) Malacostraca and ostracods	77.00	12.50	1.25	8.75
(2) Balanus	98.50	1.50	......	......
Sea-urchin spines	90.00	9.00	1.00	......
Worm-tubes	91.00	8.00	......	1.00

Chemical Composition of Corallinaceæ from Murray Island and Cocos-Keeling Islands

(By Alfred A. Chambers)

Chemical analyses of calcareous algæ

	Goniolithon frutescens Fosl., Cocos-Keeling Islands.	*Goniolithon orthoblastum* (Heyd.), M. A. Howe, Murray Island Australia.	*Lithophyllum kaiseri* Heyd., Cocos-Keeling Islands.
Loss on ignition	46.70	50.97	45.72
$SiO_2+Fe_2O_3+Al_2O_3$	.07	.11	.28
CaO	46.16	42.39	45.92
MgO	6.29	5.71	7.09
P_2O_5	Present.	Present.	Present.
SO_3	None.	None.	None.
Total	99.22	99.18	99.01
CO_2 needed	43.19	39.59	43.88

Reduced analyses (hypothetical combinations)

$SiO_2, (Al, Fe)_2O_3$	0.07	0.12	0.29
$MgCO_3$	13.80	13.66	15.33
$CaCO_3$	86.13	86.22	84.38
$Ca_3P_2O_8$	Trace.	Trace.	Trace.
$CaSO_4$	.00	.00	.00
Total	100.00	100.00	100.00

Chemical Analyses of Foraminifera important as Contributors to Deposits in Coral-reef Areas

(1) *Tinoporus baculatus* (Montfort) Carpenter, from Murray Island.
(2) *Polytrema mineaceum* (Linn.), from Cocoanut Point, Andros Island, Bahamas.
(3) *Orbiculina adunca* (Fichtel and Moll), from Key West, Florida.
(4) *Orbitolites marginalis* (Lam.), from south of Tortugas, depth 17 fathoms.
(5) *Quinqueloculina auberiana* d'Orbigny, from south of Tortugas, depth 17 fathoms.

Analyses of 1, 2, 3, 4 by W. C. Wheeler; of 5 by Alfred A. Chambers

Chemical analyses of foraminifera

	(1) Tinoporus.	(2) Polytrema.	(3) Orbiculina.	(4) Orbitolites.	(5) Quinque-loculina.
SiO_2	0.03	0.02	0.11	0.30	0.54
$(Al, Fe)_2O_3$	.18		.09	.13	
MgO	5.03	5.09	4.64	4.93	4.32
CaO	27.35	47.35	48.79	48.92	49.02
P_2O_5	.00	(?)	Trace.	Trace.	(?)
Ignition [12]	46.57	46.24	45.56	45.20	45.54
Total	99.16	98.70	99.09	99.48	98.42

Reduced analyses (hypothetical combinations)

	(1) Tinoporus.	(2) Polytrema.	(3) Orbiculina.	(4) Orbitolites.	(5) Quinque-loculina.
SiO_2	0.03	0.02	0.11	0.31	0.56
$(Al, Fe)_2O_3$	.19		.09	.13	
$MgCO_3$	11.08	11.22	10.04	10.55	9.33
$CaCO_3$	88.70	88.76	89.76	89.01	90.11
$Ca_3P_2O_8$	.00	(?)	Trace.	Trace.	(?)
Total	100.00	100.00	100.00	100.00	100.00
	Murray Id.	Bahamas.	Key West.	Tortugas.	Tortugas.

Doctor Goldman undertook at my request a study of two bottom samples from Murray Island, Australia, and endeavored to correlate the chemical composition of each sample as deduced from the organic remains composing it with the chemical composition of the entire sample as determined by actual analysis.

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[12] Equals organic matter + CO_2 + H_2O.

Summary of Analysis of organic Composition of Sample No. 27337, from Murray Island, Australia

I. Numbers of grains of different organisms counted

	Algæ.	Corals.	Mollusks.	Tinoporus.	Amphistegina.	Orbitolites.	Undifferentiated foraminifera.	Crustacea.	Balanus.	Worm-tubes.	Total.
Fine gravel....	39	31	29	5	4	2	..	..	..	..	110
Coarse sand....	56	58	20	2	1	1	3	2	..	1	144
Medium sand..	11	20	5	..	..	1	1	..	..	1	39
Fine sand.....	21	20	9	..	..	..	2	..	1	..	53
Very fine sand.	6	11	2	..	..	..	..	..	..	..	19
Total...	133	140	65	7	5	4	6	2	1	2	365

II. Calculated percentage by weight of different organisms present

	Algæ.	Corals.	Mollusks.	Tinoporus.	Amphistegina.	Orbitolites.	Undifferentiated foraminifera.	Crustacea.	Balanus.	Worm-tubes.	Total.
Fine gravel....	9.4	6.3	6.5	0.8	0.5	0.2	..	..	..	..	..
Coarse sand....	19.3	13.3	3.3	.4	.1	.3	0.6	0.4	..	0.1	..
Medium sand..	3.8	6.2	1.5	..	..	.3	.2	..	..	.1	..
Fine sand.....	9.8	8.4	3.8	..	..	..	.7	..	0.6	..	..
Very fine sand.	.2	.4	.1	..	..	..	..	..	..	..	..
Total...	42.5	34.6	15.2	1.2	.6	.8	1.5	.4	.6	.2	97.6

III. Calculated percentage chemical composition by organisms

	Algæ.	Corals.	Mollusks.	Tinoporus.	Amphistegina.	Orbitolites.	Undifferentiated foraminifera.	Crustacea.	Balanus.	Worm-tubes.	Total.
$CaCO_3$.........	38.0	34.4	15.2	1.0	0.6	0.7	1.3	0.3	0.6	0.2	92.3
$MgCO_3$........	4.2	.2	.0	.2	.0	.1	.2	.1	.0	.0	5.0
$CaSO_4$.........	.3	...	...	..	..	..	..	..	..	..	.3
$Ca_3P_2O_8$.......	...	...	...	..	..	..	..	..	..	..	..

IV. Calculated percentage chemical composition by size portions

	Per cent present.	$CaCO_3$.	$MgCO_3$.	$CaSO_4$.	$Ca_3P_2O_8$.
Fine gravel....................	23.6	22.40	1.10	0.3	....
Coarse sand....................	37.9	35.55	2.20	....	Tr.
Medium sand..................	12.2	11.70	.50	....	Tr.
Fine sand.......................	23.2	22.00	1.15	....	....
Very fine sand.................	.7	.65	.05	....	....
	97.6	92.3	5.00	0.3	Tr.
Silt............................	.7	1.7	Tr.	....	....
Clay...........................	1.2	1.7	Tr.	....	....
Total....................	99.5	93.7	5.0	0.3	....

Chemical Composition of Samples from Murray Island, Australia, as calculated from their organic Ingredients and as determined by chemical Analysis

Specimen No. 27353*a*, 1,600 feet from shore

	$CaCO_3$.	$MgCO_3$.	$CaSO_4$.	$Ca_3P_2O_8$.	SiO_2 and $(Al, Fe)_2O_3$.
Calculated	94.3	4.6	0.2	Tr.	.60
Observed	93.6	5.8	Tr.	...	.60

	$CaCO_3$.	$MgCO_3$.	$CaSO_4$.
Revised	93.0	5.8	0.2
Observed	93.6	5.8	Tr.

Specimen No. 27337, 200 feet from shore

	$CaCO_3$.	$MgCO_3$.	$CaSO_4$.	$Ca_3P_2O_8$.	SiO_2 and $(Al, Fe)_2O_3$.
Calculated	93.7	5.0	0.3	Tr.	0.63
Observed	93.85	5.5	Tr.	.00	.63

	$CaCO_3$.	$MgCO_3$.	$CaSO_4$.
Revised	93.15	5.5	0.3
Observed	93.85	5.5	Tr.

The relative importance of organisms in the samples from Murray Island is as follows: 1,600 feet from shore, madreporarian corals, 41.9 per cent; calcareous algæ, 32.6 per cent; foraminifera, 12.4 per cent; mollusca, 10.2 per cent. At 200 feet from shore the order is: Calcareous algæ, 42.5 per cent; madreporarian corals, 34.6 per cent; mollusca, 15.2 per cent; foraminifera, 4.1 per cent.

The next two tables will bring out the similarity between the material from behind the reef at Murray Island and that from behind the reef at Cocoanut Point, Andros Island, Bahamas.

Percentages of Particles of Silt and Clay Size in bottom Samples from the Reefs at Murray Island, Australia, and at Cocoanut Point, Andros Island, Bahamas.

Murray Island	Per cent	Cocoanut Point	Per cent
200 feet from shore	1.9	Sample 190	1.5
600 feet from shore	2.8	191	1.8
1,200 feet from shore	.9	192	1.7
1,600 feet from shore	1.4	193	1.9
Average	1.75	Average	1.725

Remarks.—It should be noted that as fine and medium sand are predominant in the Cocoanut Point samples, they average finer than the Murray Island specimens.

Percentage of $MgCO_3$ (hypothetical Combination) in Samples considered in preceding Table

Murray Island	Per cent	Cocoanut Point	Per cent
200 feet from shore	5.52	Composite of samples 190 to 193	5.24
600 feet from shore	5.95		
1,200 feet from shore	5.76		
1,600 feet from shore	5.83		
Average	5.745	Average	5.24

Material such as that on and behind the coral reefs at Murray Island, Australia, and Cocoanut Point, Bahamas, are predominantly composed of the remains of madreporarian corals and calcareous algæ; in some places the remains of one, in other places the remains of the other, group of organisms predominating. Grains derived from these two sources form between 74 and 76 per cent of the material across the Murray Island reef, while, roughly, from 20 to 23 per cent is due to mollusca and to shoal-water, bottom-living foraminifera. There is very little pelagic material, although it should be mentioned that coccolithophoridæ are invariably present at each locality in separates of silt and clay size. There is an important difference between the Murray Island and Cocoanut Point samples in that those from Murray Island contain no alcyonarian spicules, while there are many such spicules in the material from Cocoanut Point.

Deposits of the kind just described are dependent on definite, areally limited, ecologic conditions; and, according to present information, they cover relatively small areas. In other areas molluscan remains predominate; in others tests of foraminifera, while in others there are relatively few organic remains and the material is mostly a chemical precipitate. Large deposits of calcium carbonate formed by the secreting activities of organisms, as well as those deposits formed by chemical precipitation, are found in the warmer parts of the ocean, or at least where the surface temperature is high.

CONCLUSION

The investigations outlined comprise ascertaining the physical and chemical characters of a deposit, analyzing it to discover the source of each constituent, evaluating each constituent, and classifying the deposit according to the source of its constituents. The physico-chemical conditions that determine the presence of the responsible depositing agencies in each particular spot must be ascertained and deposits formed under different physico-chemical conditions must be compared. By following such a procedure we may hope to understand what is now happening in the sea, and the knowledge thus gained may enable us to make dependable deductions regarding the history of the sediments that engage our attention in our geologic researches.

EXPLANATION OF PLATES

PLATE 47.—*Artificial Spherulites and Oolites*

FIGURE 1.—Spherulites bacterially formed in water from Great Salt Lake. × 100. (Preparation by K. F. Kellerman.)

FIGURE 2.—Spherulites bacterially formed from calcium acetate in water from Great Salt Lake. × 50. (Preparation by K. F. Kellerman.)

FIGURE 3.—Zonal spherulite inorganically formed in sea-water from Florida. × 350.

FIGURE 4.—Zonal spherulites inorganically formed in sea-water from Florida. × 700.

PLATE 47.—*Natural Precipitates*

FIGURE 5.—Great Salt Lake oolite. × 100.

FIGURE 6.—Aragonite needles out of mud from the west side of Andros Island. × 840.

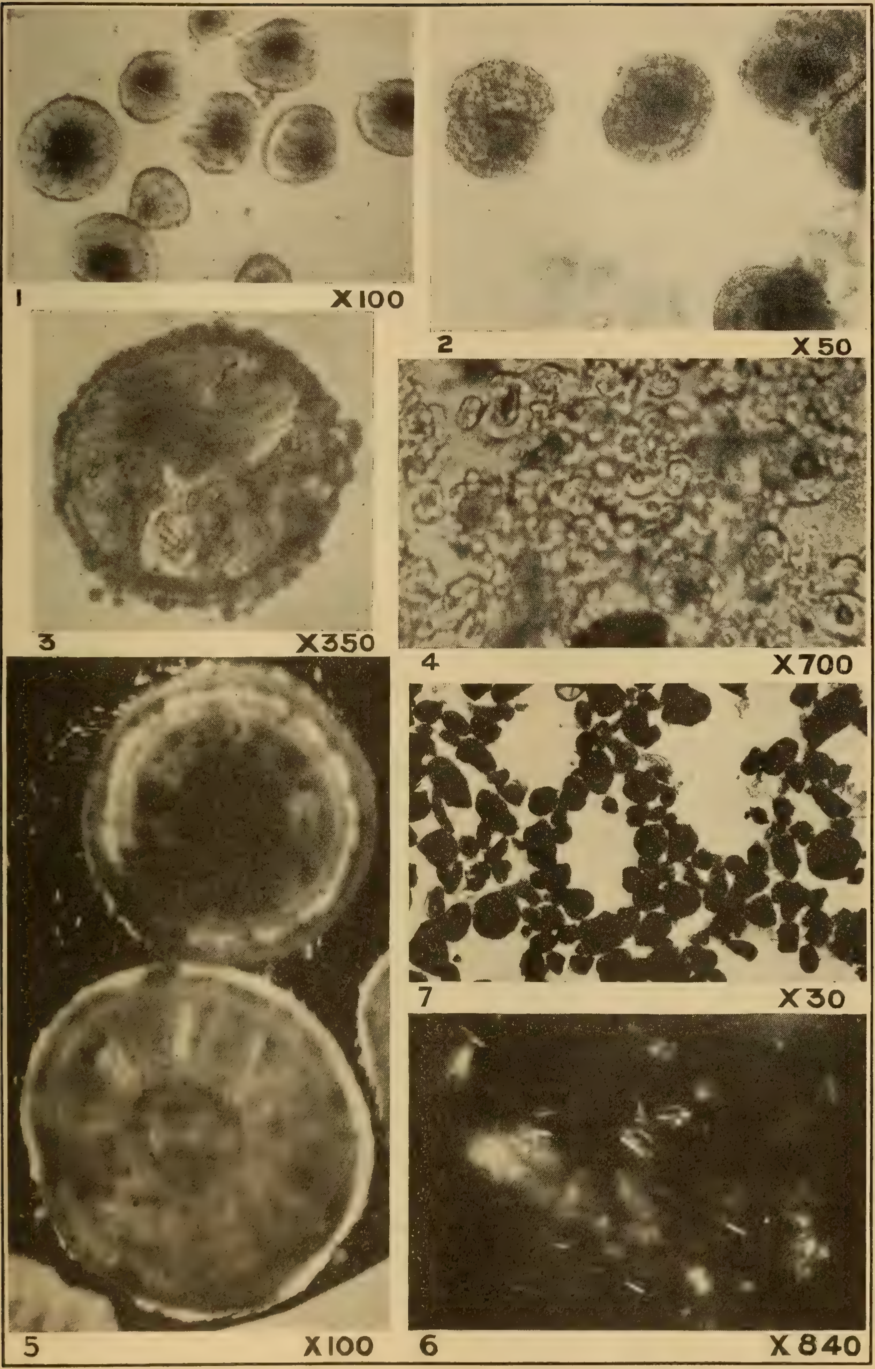
FIGURE 7.—Small oolites out of mud from the west side of Andros Island. × 30.

PLATE 48

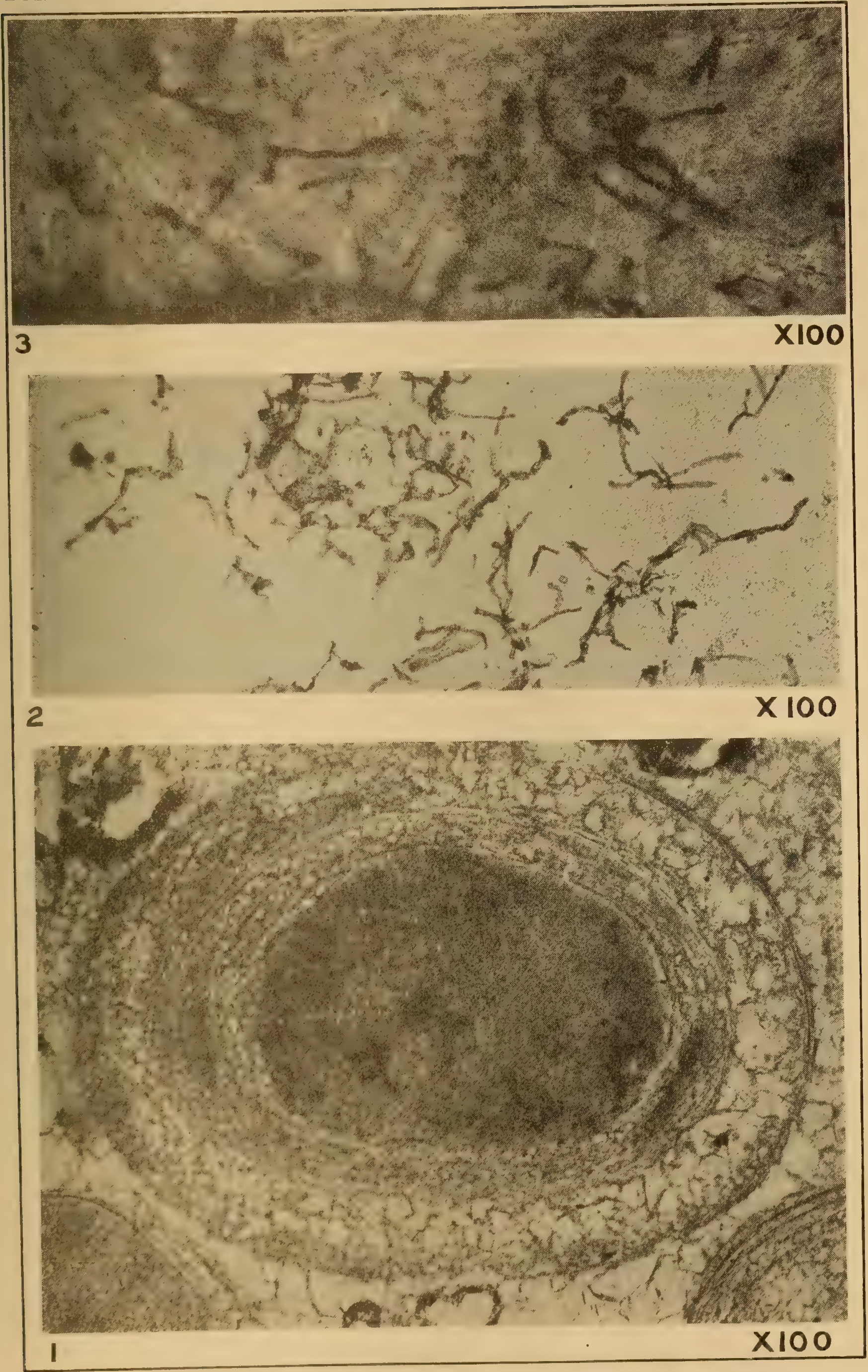
FIGURE 1.—Bahaman elevated oolite. × 100, without traces of filamentous algæ.

FIGURE 2.—Illustrates filamentous algæ left after decalcification of a corallite of *Orbicella cavernosa* (Linn.). × 100.

FIGURE 3.—Thin section of *Orbicella annularis* (Ellis and Solander), with filamentous algæ in place. × 100. The presence of filamentous algæ in oolite grains is adventitious. These organisms bore into any calcium-carbonate structures that lie on the sea-bottom.


1
X100
2
X50
3
X350
4
X700
5
X100
7
X30
6
X840

ARTIFICIALLY AND NATURALLY PRECIPITATED CALCIUM CARBONATE


3
X100
2
X 100
1
X100

FILAMENTOUS ALGAE THAT BORE INTO CORAL SKELETONS AND OOLITE GRAIN WITHOUT FILAMENTOUS ALGAE

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 28, PP. 945-958 DECEMBER 19, 1917
PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY

STRATIGRAPHIC RELATIONSHIPS OF THE TULLY LIMESTONE AND THE GENESEE SHALE IN EASTERN NORTH AMERICA[1]

BY AMADEUS W. GRABAU

(*Presented before the Paleontological Society December 29, 1916*)

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CHARACTER AND DISTRIBUTION OF THE TULLY LIMESTONE

In its type locality near Tully, in the central part of New York State, the Tully limestone has a thickness of about 23½ feet and rests conformably on the Upper Hamilton (Moscow) shales. The contact between the two is well shown in the cliff of Tinkers Falls, several miles east of Tully, and appears to be an absolutely gradational one. This is shown by the fact that the somewhat sandy shales of the Upper Moscow gradually become finer and more calcareous and beds of a more strongly limy character alternate with layers of more argillaceous material. Finally, the lime entirely replaces the clay and the impure Tully limestone is developed. The contact is thus a transitional one, and the Tully must be regarded as marking the passage of sedimentation without break from the Middle to the Upper Devonic. The faunas, too, partake of this transitional character, as is shown by the fact that the majority of species found in the Tully limestone are forms equally characteristic of the Upper Hamilton (Moscow) shales of central New York, only a comparatively small proportion being of types newly added.

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[1] Manuscript received by the Secretary of the Geological Society July 25, 1917.

In the Tully region the Moscow shale, which underlies the Tully and is stratigraphically continuous with it, has a thickness of 180 feet and rests directly and conformably on the Upper Ludlowville shales, but farther west these two formations are separated by the Tichenor limestone. The Tichenor is the "Encrinal limestone" of the early New York surveys; but the name "Encrinal" has also been used for a similar limestone which is wide-spread in western New York and which is well shown in the exposures on the shore of Lake Erie, north and south of Eighteen Mile Creek, and in the gorge of that stream. This limestone, for which I propose the name *Morse Creek limestone,* from Morse Creek, near Athol Springs, Erie County, New York, lies in reality below the horizon of the Ludlowville shale and is the equivalent of the Centerfield limestone of the Cayuga Lake region. The Tichenor limestone is represented by the *Menteth* limestone, in the Genesee Valley region, but is not seen in western New York, where the Ludlowville and Moscow together are reduced to a thickness of 17 feet at Eighteen Mile Creek. For this 17-foot formation, which has commonly, but erroneously, been called the Moscow shale, I propose the name *Windom shale,* from the exposures of this rock near the village of Windom, in Erie County. The significance of these stratigraphic variations within the State will be discussed in another paper.

In western New York the Tully is scarcely represented, although there is a very persistent, calcareous bed, four inches thick and only a few inches below the top of the Windom shale at Eighteen Mile Creek and on the Lake Erie shore, which may indicate the Tully type of sedimentation. As I have shown elsewhere, it[2] and the shales which overlie it, carry a fauna, in part at least, suggestive of Naples affinities, with *Schizobolus truncatus* a dominant member. *Spirifer tullius,* however, also occurs here, and *Leiorhynchus multicostatus* and *Ambocœlia præumbona* are abundant. The Tully horizon is, however, represented a few miles to the east, in Erie County, by a pyrite layer up to four inches in thickness and generally of a lenticular character. This is seen at Spring Brook, on the banks of Cazenovia Creek, and its character is essentially like that of the Tully pyrite layer of the Genesee Valley, noted below. It contains an abundance of pyritized fossils.[3]

The Windom is succeeded at Eighteen Mile Creek by an inch or two of Genesee shale, which carries *Styliolina fissurella,* conodonts and the spore *Protosalvinia huronensis.* Above this lies the Styliolina limestone, which here includes about four inches of the remarkable *Conodont limestone* at the base.

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[2] Geology and Paleontology, Eighteen Mile Creek.

[3] F. Houghton: The geology of Erie County. Bull. Buffalo Soc. Nat. Sci., vol. xi, p. 32.

Two miles south of the mouth of Eighteen Mile Creek the Genesee shale has a thickness of 12 inches and is followed by the Styliolina (Genundewa) limestone, the conodont phase being absent. Farther east, in Erie County, this shale thickens. Thus at Spring Brook it is from 19 to 26 inches thick and increases regularly east of this point.

West of Buffalo both the Tully and the Genesee are absent, and the Portage shales lie with a disconformable contact on the eroded surface of the Upper Hamilton. In western Ontario the beds above the Morse Creek limestone (the equivalent of the Ludlowville and Moscow shales of central New York) thicken to 150 feet, but in northern Ohio erosion in Upper Devonic time had removed all the beds above the Prout limestone, the probable equivalent, according to Stauffer, of the Encrinal (Morse Creek) limestone of western New York. This erosion occurred, of course, prior to the deposition of the black Portage (Ohio) shales. The disconformity between the Ohio (Portage) shales and the Hamilton beds is traceable throughout Ohio, Indiana, Kentucky, Michigan, Wisconsin, Illinois, and westward, becoming in general greater toward the south. This implies, then, that during early Upper Devonic time—that is, during the period of deposition of the Tully and the Genesee of New York—the region west of New York was dry land and subject to erosion.

In the Genesee Valley the Tully is represented by a pyrite layer a few inches in thickness, which contains the dwarfed fauna described by Loomis.[4] This fauna still shows nearly 75 per cent of Hamilton species, all, however, occurring as dwarfed varieties and which were clearly derived from the rich Hamilton fauna of the underlying Moscow shales, though their size averages only one-fifteenth that of the normal. The Genesee shale here is 82 feet thick, and the pyrite layer marks the final change in sedimentation, although the upper four or five feet of the Moscow show a transition from the open and pure-water condition, in which the rich Hamilton fauna lived to a muddy sea, with a much reduced fauna. The pyrite layer finally marks the development of shallow pools with stagnant water and the liberation of much sulphur; but these pools were later destroyed by the influx of the black muds, which constitute the Genesee formation. As has been noted above, this pyrite layer can be traced west into Erie County.

The Tully limestone of the type region is for the most part a bedded calcilutyte, in which fossils occur sporadically, but are on the whole rather infrequent. A noteworthy fact is that the fossils that do occur are all complete, and themselves added very little to the substance of the rock. Recognizable fragments of organisms are wanting; only perfect forms occur embedded in a fine lime mud. It is obvious, then, that the Tully limestone could not have been formed from the remains of shells and other calcareous organisms broken *in situ,* but that the lime mud must have had a different origin, or else have been transported by currents to this region from a distant point of origin. Chemical precipitation or the growth and destruction of calcareous algæ might account for a lime accumulation of this kind, but thin sections of the rock show no evidence of structure which would lend plausibility to either conclusion. The rock has the characteristics of a fine lime mud, apparently of clastic origin. Nor are there anywhere in this region residual masses of algal origin, such as generally are to be found in regions where limestones are formed by these agencies.

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[4] New York State Museum. Report of the State Paleontologist for 1902, pp. 892-920, with plates; 1903.

It appears, then, that the lime mud, of which the Tully limestone consists, had its origin in some other region and was brought to its present resting place by the currents of the Tully sea. The source of the lime might be either an older limestone, the destruction of which furnished the lime, or a reef mass of algal, coral, or other origin, the erosion of which could furnish the lime. The first of these sources is negatived by the fact that the formations subject to erosion during Tully time were mostly argillaceous and siliceous sediments, calcareous beds being sparingly represented in these formations. It would thus be impossible to account for the comparative purity of the Tully limestone, as well as for the absence of corresponding argillaceous and siliceous sediments into which the limestone should grade laterally. The reef theory is open to no such objections, for all that is necessary to assume is that the drainage from the Hamilton lands, which were subject to erosion at that time, was carried into another portion of the sea, where it could not interfere with the development of a relatively pure limestone mass. Since lime muds of the type which forms the Tully limestone can be carried in the sea for great distances, the reef which was their source might have been far removed from the present line of outcrop of these limestones, and indeed might since have been entirely destroyed by erosion.

Traced eastward from Tully, along the outcrop, the limestone is seen to diminish in thickness with relative regularity, until it has disappeared entirely as a limestone in the meridian of Smyrna, in Chenango County. Prosser has been able, however, to trace the Tully fauna for a considerable distance east of this point, its chief diagnostic member, *Hypothyris cuboides,* occurring in a layer at the top of the Hamilton and just below the beds which mark the inauguration of Sherburne conditions of sedimentation.

East of Smyrna the Hamilton is succeeded conformably by the Sherburne sandstone, which carries only plant remains and which apparently originated as a low bar, which at the beginning of Upper Devonic time divided the Tully sea from a water body to the west in which the Ithaca fauna developed.[5] It is thus evident that the Tully sediment could not have been derived from the east any more than it could have been derived from the west, where lay the shallow pools in which the iron pyrite layer was forming; but no such objection applies to the north, where the former continuation of this rock has been removed by erosion.

Relationship of the Tully Limestone and Genesee Shale

The Genesee black shale everywhere succeeds the Tully limestone. It is 75 feet thick at Tully, where it seems to succeed the limestone somewhat abruptly, though no actual contact has been observed. It is thence traceable eastward to about the meridian of Smyrna, in Chenango County, or as far as the Tully limestone is developed, beyond which point it disappears and is replaced by the sands of the Sherburne formation. The abrupt change from the shale to the sandstone precludes the possibility that the muds of the Genesee were derived from this eastern region. These relations are shown in figure 1, page 950, which represents an east-west section through New York State. As we have seen, the Genesee shale thins regularly westward, until in eastern Erie County it is only about two feet thick and at Eighteen Mile Creek less than an inch. Evidently the source of the black mud could not have been in the west. It could not have been to the north, if that was the source of the limestone mud of the Tully, and hence we must regard the south as the only possible source of the deposit. This is indeed shown to be the case by the gradual thickening of the Genesee southward, with a corresponding decrease in the thickness of the Tully limestone which underlies it. The section of the Tully and the Genesee exposed on Cayuga Lake, a few miles north of Ithaca, is extremely instructive in this connection. Through the kindness of Prof. G. D. Harris, I was enabled to study this section in some detail. The total thickness of the Genesee is here 135 feet, and it is capped by an arenaceo-calcareous layer from one to two feet thick, which contains many pyrite concretions. This probably represents the horizon of the Genundewa limestone, though it is generally not composed of Sty-

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[5] The Sherburne problem is discussed in another paper.

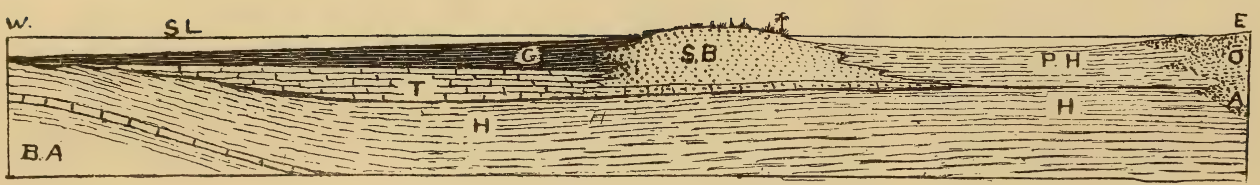

FIGURE 1.—*West-East Section of New York State*

Showing the position of the Sherburne bar (S. B.), the Tully limestone (T.), Genesee shale (G.). A. = Ashokan or continental Hamilton. B. A. = Buffalo axis. H. = Hamilton. O. = Oneonta. P. H. = Post-Hamilton (early Portage beds with Hamilton fauna). S. L. Sealevel in Genesee time.

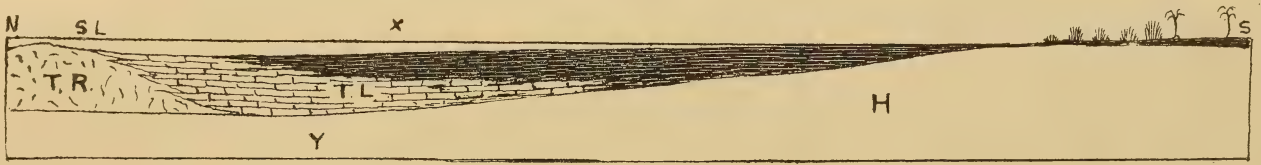

FIGURE 2.—*North-South Section from Canada across New York to Maryland*

H. = Hamilton bed. T. L. = Tully limestone. T. R. = Tully reef. S. L. = Sealevel in Tully-Genesee time. On the south (right) is shown the low lands adjoining the Romney River covered by black earth (tchernozem), which was the source of the Genesee muds. X. Y. = line of present outcrop.

liolina shells. The basal part of the Genesee is well shown on the western bank, where the Tully band, rising northward from the water, makes a prominent cliff. The black shale can be seen to grade downward into gray, calcareous shales in which Chonetes and Orthoceras occur. The rock is still a shale, but some layers are resistant enough to form shelves at the water level. These layers are generally about six inches thick and are separated by fissile shale layers, which layers are in general of a blacker color than the harder, more calcareous beds, though their color is not as deep as that of the typical Genesee. Downward the calcareous layers become more solid and the shales separating them are less black in color. The entire thickness of this transition series is about eight feet and below it the Tully limestone proper occurs. This rests on the fossiliferous Moscow shales, which in turn are underlain by the Tichenor limestone. It is here very evident that the contact of the Tully and the Genesee is a gradational one, the Genesee type of sedimentation gradually replacing the Tully type; also, since only the lower part of the Tully is calcareous in the Ithaca region, the upper part must be represented by the Genesee type of sedimentation. From this it appears that the Genesee type of sediment was gradually and progressively replacing the Tully type to the northward.

SOUTHWARD DISAPPEARANCE OF THE TULLY LIMESTONE

The Tully limestone disappears entirely a short distance south of the Pennsylvania line, beyond which only black shale of the Genesee type is found.

In the Catawissa section of Columbia County, Pennsylvania, the Hamilton group is terminated by a somewhat calcareous series 25 feet in thickness, with a normal Hamilton fauna. This is succeeded by 225 feet of bluish black fissile shales, which have the character of the Genesee and are to all appearance barren of fossils. This, in turn, is succeeded by 25 feet of dark blue, shaly sandy beds without fossils, which represent the closing stages of Sherburne sedimentation. Next above this are 175 feet of shales and sands carrying the Naples fauna and with many included plant remains, and then follow 1,400 feet of shales in which the Ithaca fauna holds sway.

This section is due south of Ithaca, and it apparently marks the line of maximum deposition of the Genesee type of sediment. It is significant of the conditions of the sedimentation that marine fossils are on the whole very rare in these shales, while plant fragments and spores are not uncommon.

In Allegany and Washington counties, Maryland, black shale deposition began in Onondaga-Marcellus time, continuing throughout the Hamilton with little change. This constitutes the Romney formation, which has been subdivided into an Onondaga member of dark shales and thin limestones at the base, 100 to 150 feet thick, a Marcellus member of black fissile shales about 500 feet thick in the middle, and a Hamilton member at the top. This last is about 1,000 feet thick, and is composed of dark shales often somewhat sandy, and carries several heavy sandstones in its upper portion.

In Allegany County these upper Romney beds are abruptly succeeded by black fissile shales about 90 feet in thickness, which carry a Naples fauna, comprising *Buchiola retrostriata, Pterochænia fragilis, Styliolina fissurella, Bactrites aciculus,* etcetera.[6] This formation has been correlated with the Genesee of New York, but probably does not represent the typical Genesee. It may, however, represent the West River shales of New York which overlie the Gennundewa limestone or the Middlesex black shales which succeed these. Farther east in Washington County, Maryland, these black shales are wanting, and the olive shales and sandstones of the higher Jennings formation rest directly upon the Romney.

ORIGIN OF THE GENESEE SHALE

From what has so far been given, it is clear that the source of the sediment which composes the Genesee formation was to the south, and that the thicker series of these beds in Pennsylvania point to continuous mud deposition there, while the calcareous sediments, which formed the Tully limestone, were accumulating over much of New York State. The increasing spread of the black muds from the south finally put an end to deposition of calcareous muds from the north, and thus black Genesee shale came to overlie the Tully limestone. How far beyond the present northern line of outcrop the Genesee sedimentation extended, whether it reached the region of the reefs which furnished the lime mud of the Tully limestone, will forever remain an unsolved problem, since these reefs, if such they were, have been wholly removed by post-Paleozoic peneplanation. Their position was probably somewhere in Canada north of Lake Ontario.

From the relation of the Genesee sediments to the other formations, it is apparent that these muds could have been supplied only by a river which entered the Upper Devonic sea from the south. It is probable that Maryland was at this time above water, but so low that little erosion was taking place. From the thick character of the muds in eastern Pennsylvania it would appear that this part of the State was comprised within the estuary in which these black muds were laid down. That the waters of this estuary were more fresh than salt is indicated by the scarcity of marine organisms and by the dwarfed character of those that are found. The source of the mud must have been in a region of low relief, where residual soils rich in decaying vegetation were developing. Such regions appear to have existed over part of the present southern Appalachian region at the beginning of Upper Devonic time—existed, in fact, during Middle Devonic time as well. The rivers which washed these muds into the Genesee estuary, which covered part of Pennsylvania and New York, also brought remains of the land vegetation in the form of tree trunks and spores.

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[6] Maryland Geological Survey. Middle and Upper Devonian, 1913, p. 347.

We have a modern example of such a type of deposit in the drainage basin of the Vistula River of Europe. This river drains the comparatively flat country of Poland and eastern Prussia, and carries its sediment into the Bay of Dantzig, on the south coast of the Baltic. The salinity of the waters of this bay is very low, being on the average only 7.22 per mille for the surface and 11.66 per mille at a depth of 105 meters. The marine life of this bay is of a limited and depauperate type, with a dwarfing of those euryhaline individuals which are found. According to G. Bishof,[7] the mud brought down by the Vistula loses 23.3 per cent on ignition, most of this being organic material. As deposited on the floor of the bay, the mud is of such a deep black color that it is locally called pitch. It covers an area of 615 square miles on the bottom of the bay.

The Genesee estuary was apparently flooded by an advance of the ocean waters from the north after the Genesee muds had been deposited. This is indicated by the increase in the frequency of marine organisms in the succeeding West River and Middlesex shales. The muds were still carried in by the rivers, but the salinity seems to have increased considerably. Of especial interest is the sudden precipitation of millions of pelagic shells of *Styliolina fissurella,* which accumulated in such quantities as to form limestone beds often 6 inches or more in thickness and of great east and west extent. Dr. John M. Clarke has estimated that this limestone sometimes contains as many as 40,000 individual shells to the cubic inch. This enormous precipitation was apparently brought about by the influx of the plankton-bearing currents into the brackish estuaries and the consequent killing of these stenohaline organisms by the millions. The intercalated black shales and the presence of plant remains and of plates of fishes, probably of river types, in the limestone layers show that the rivers were still bringing in sediments and organic remains from the south.

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[7] Lehrbuch der Chem. u. phys. Geologie I.

This advance of the sea apparently flooded the region in Allegany County, Maryland, and converted it into the estuary in which were deposited the black Portage muds, which are continued on into New York as the West River and Middlesex shales. These shales thin westward, as does the Genesee, but they extend farther than the latter as the result of the transgression of the sea over the former land-masses. The origin of the West River, and especially the black Middlesex shale, is apparently to be sought in the same river systems which furnished the mud for the Genesee shale. The higher black shales of the Portage, however, thicken toward the west—a reasonable indication that the source of supply of this material is to be sought for in that direction. Indeed, we now know that the upper black Portage shales are the eastward continuations of the Ohio shale series, which likewise had its origin in the south, but in another river system situated farther to the west. These higher black shales and their significance have been fully discussed in the report on the Devonic submitted to the Geological Survey of Michigan.

It must be borne in mind that throughout the Genesee period, as well as during the period of deposition of the West River and Middlesex shales, the basin in which these deposits were forming was limited on the east by the Sherburne bar, now represented by that part of the Sherburne sandstone which carries only plant remains and the distribution of which is approximately outlined by the area inclosed between the Chenango and the Unadilla rivers of New York. East of this bar the Hamilton fauna continued through the lower 200 feet of Portage beds. Still farther east the continental sediments of the Oneonta sandstone were accumulating on the sea margin as part of a long-continued delta deposit. These rest upon shales and sands 500 or 600 feet in thickness, which represent the non-marine terminal phase of the Hamilton. These shales and flags contain no fossils other than plant remains, and they pass downward into the normal fossiliferous marine Hamilton, as can be seen in the cut of the Ulster and Delaware Railroad east of West Hurley Station. I propose to name the lower fossiliferous Hamilton beds of the Ulster County region the *Mt. Marion beds*, and the higher, non-marine series, the *Ashokan beds*. It is this latter series which Prosser erroneously called Sherburne in his monograph on the Hamilton and Portage beds of eastern New York.[8] The Ashokan series forms the principal bluestone formation

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[8] New York State Museum. Seventeenth Annual Report of the State Geologist, 1899.

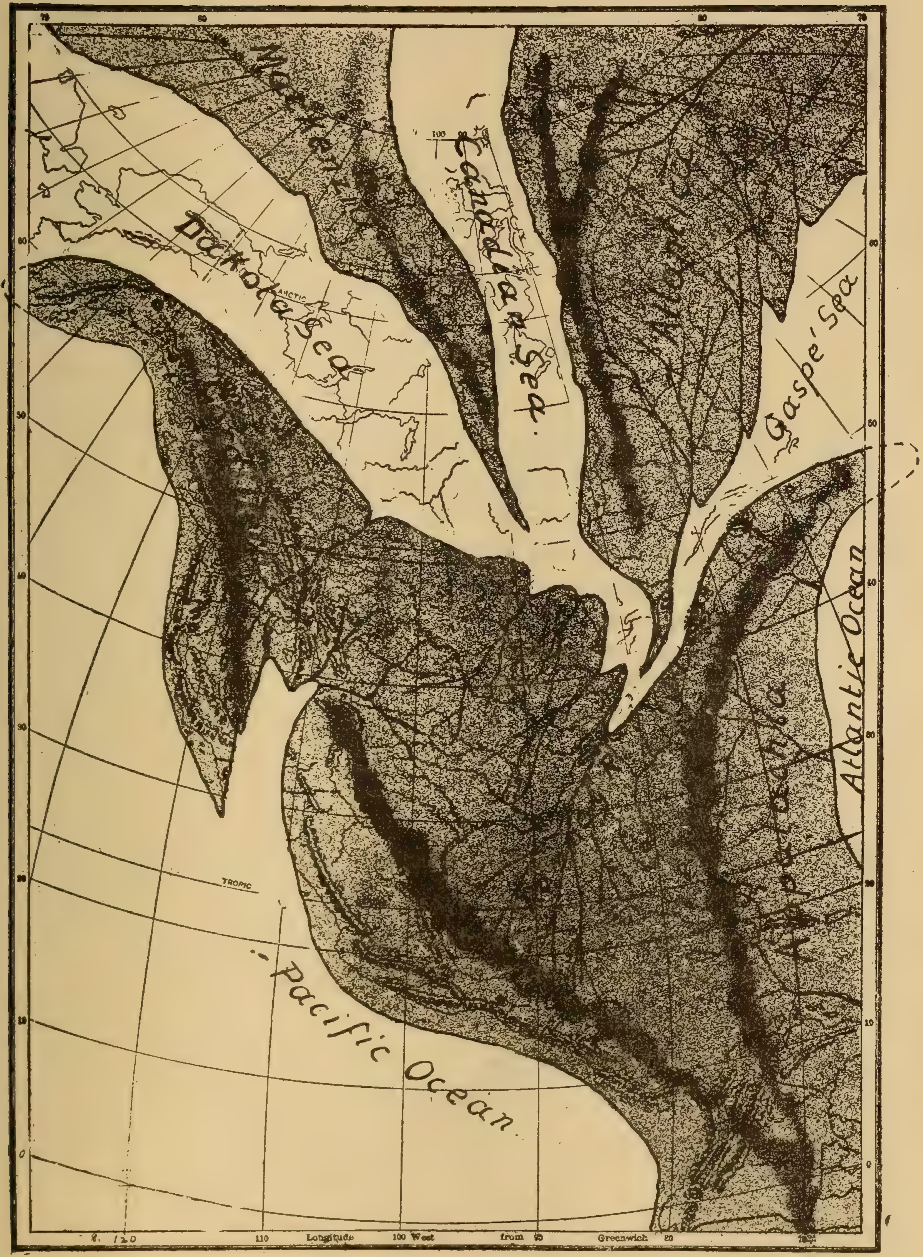
Mackenzia
Dakota Sea
Canadian Sea
Gaspé Sea
Atlantic Ocean
Appalachia
Pacific Ocean
ARCTIC
TROPIC
120
110
Longitude
100 West
from 90
Greenwich
80
70

FIGURE 3.—*Paleogeographic Map of Tully Time*

of Ulster County, though good bluestone is also found in the overlying Oneonta. Tully and Genesee sedimentation are entirely wanting in the eastern basin, both the sediments and the faunas being kept out by the Sherburne bar.

The north-south section (figure 2, page 950), together with the east-west section (figure 1, page 950), will make clear the conditions of things which existed in Upper Devonic time in the eastern section of North America, and the map (figure 3) is an attempt at depicting the physiography of North America in Tully time.

THE TULLY FAUNA

The fauna of the Tully limestone of New York is a composite one, consisting in part of (1) unmodified or persistent Hamilton species, in part of (2) species of the Hamilton fauna modified *in situ,* and in part of (3) immigrant species. Of the first group (1) we may mention:

1. *Ambocœlia umbonata.*
2. *Atrypa reticularis.*
3. *Atrypa spinosa.*
4. *Cyrtina hamiltonensis.*
5. *Schuchertella arctostriata.*
6. *Spirifer fimbriatus.*
7. *Spirifer tullius.*
8. *Cryphæus boothi.*
9. *Phacops bufo.*

and species of Hamilton gastropods, pelecypods, cephalopods, and corals.

(2) Species modified apparently in this region from the Hamilton fauna, which was cut off from its source of supply by the development of the Sherburne bar, comprise the following significant forms:

1. *Chonetes aurora* Hall.

This is known only from this horizon and has not been found outside of the State. It is probably a Hamilton derivative.

2. *Productella spinulicosta* var. *tulliensis* H. S. Williams.

A local modification of the characteristic Hamilton species.

3. *Spirifer mucronatus* var. *tulliensis* H. S. Williams.

Transitional, according to Williams, from the Hamilton form to the *S. mesicostalis,* probably through *S. mucronatus* var. *posterus.*

4. *Stropheodonta perplana* var. *tulliensis* H. S. Williams.

This, according to Williams, is a derivative of *S. perplana* of the Hamilton, leading from that to *S. mucronata* of the Ithaca.

5. *Platyceras symmetricum* var.

A modification of the Hamilton form.

(3) The most significant of the immigrant species into this fauna are the following:

1. *Schizophoria tulliensis* (Vanuxem).

This is clearly an emigrant from the Iowan and Michigan Traverse fauna, where its ancestors are found.

2. *Hypothyris venustula* Hall.

This species, commonly made a varietal form of the European *H. cuboides* (Sowerby), is the most characteristic of the immigrant forms. As shown by Prosser, it was one of the first to come, while the Hamilton fauna was still in its purity and just before the building of the Sherburne Bar. In the Traverse (Wapsipinicon) of Iowa occurs the closely related *H. intermedia* Barris, which, according to Walcott, is identical with the *H. emmonsi* (Hall and Whitf.) of Nevada. It is there associated with *Gypidula comis.* I have elsewhere[9] shown that the Wapsipinicon of Iowa is essentially Lower Traverse, exclusive of the Independence shale, which may be pre-Traverse or Dundee in age. In western Europe the species associated with *Hypothyris cuboides* are either forms which for the first time have representatives in our Chemung faunas or are types which are found in the Iowan and western Michigan Traverse. Among the latter are *Pugnax pugnus* (Mart.), *Pentamerus* (*Gypidula*) *galeatus* (Dalm.), *Schizophoria striatula* (Sloth.), *Spirifer verneuili* Murch., *Atrypa concentrica, Cyathophyllum hexagonum, Prismatophyllum pentagona,* E. & H., *P. goldfussi, Phillipsastræa* (*Billingsastræa*) *verneuili* E. & H., *Favosites cervicornis,* and others. The fauna of the Mackenzie River region also shows close affinity with the Cuboides fauna of Europe, and the connection with west Europe may be traced through Asia, where *H. cuboides* has been found in China and Persia and in the Urals, Petschora land, and Poland in eastern Europe.

It is thus evident that, as pointed out by J. M. Clarke, the pathway between Europe and America along which the dispersal of *H. cuboides* occurred was the same as that which permitted the interdispersal of the Traverse and the Mid-Devonic European faunas, as well as the Upper Devonic coral and Brachiopod fauna of Europe and the Iowan Upper Devonic basin. But whether *H. cuboides* is a derivative of the American *H. intermedia,* from which *H. venustula* was also derived, and by westward migration reached Asia and Europe in Upper Devonic time, or whether our species are immigrants from Europe is not easy to determine. The fact that the European varieties are frequently characterized by a high antero-median extension, whereas the west American species are less specialized in that respect, lends some support to the interpretation that migration was westward, and that the Cuboides type originated in American waters in Hamilton (Traverse) time.

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[9] Report on the Traverse group submitted to the Michigan Geological Survey; not yet published.

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VOL. 28, PP. 959-964 DECEMBER 19, 1917
PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY

WERE THE GRAPTOLITE SHALES, AS A RULE, DEEP OR SHALLOW WATER DEPOSITS?[1]

BY AMADEUS W. GRABAU AND MARJORIE O'CONNELL

(Presented before the Paleontological Society December 28, 1916)

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INTRODUCTION

During the last four or five decades the two chief objects in the study of the graptolites have been, first, the refinement in classification, together with the careful description of new species and the determination of ontogenetic and phylogenetic relations; and, secondly, the determination of the exact stratigraphic or zonal distribution of the graptolites and the correlation of these zones over wide geographic areas. Questions of habitat and mode of distribution were considered only incidentally, though such keen students as Lapworth, Wiman, Ruedemann, and Hahn have dealt with these problems separately. The conclusions reached by Lapworth[2] and published in Walther's *"Ueber die Lebensweise fossiler Meeresthiere"* have been quite generally accepted. His belief is that the graptolites, which lead a floating existence either as holoplankton or epiplankton (attached to sea-weeds), sank to the bottom of the deeper littoral, where no other organisms lived and where they were buried in the fine mud which was rendered carbonaceous by the decaying sea-weeds. The absence of bottom organisms in these deposits is generally explained on the basis of the great depth of the water. Wiman, on the contrary, recognizing the difficulties attending Lapworth's explanation, regards the graptolites as sedentary on ocean bottoms, where no other organisms can exist. It has been pointed out by both Lapworth and Ruedemann that the graptolites may sink to the bottom nearer shore in quiet waters, for the presence of intercalated beds of sandstone and conglomerates in the graptolite-bearing shales is clear proof of the proximity to the land; but the former author states, and the latter agrees with him, that the shales in the Moffat region in Scotland were clearly deposited far from shore in comparatively deep water.

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[1] Manuscript received by the Secretary of the Geological Society April 30, 1917.

[2] Zeit. d. deutsch. geolog. Gesell., Bd. xlix, Heft ii, pp. 209-273; Lapworth's letter, pp. 241-258.

THE PROBLEM STATED

The problem before us, then, is this: Were the shales which carry only graptolites, or in which other organic remains are rare, deposited in waters too deep for other organisms to exist, or were these deposits, as a rule, formed in deltas, into the lagoons or bays of which only the planktonic organisms would in general be washed from the sea at exceptionally high tides or on the destruction of bars and similar barriers? The present preliminary note is to be regarded merely as a report of progress and it is hoped that it will stimulate discussion of the subject.

There are at least three lines of attack which might be followed in a critical study of the lithogenesis of the graptolite-bearing shales. First, there is the bionomic aspect, which is of great importance, particularly since there are living representatives of the graptolites whose habitats may be studied. A second line of attack is found in the consideration of the lithologic character of the formations in which graptolites occur. The third aspect to be considered is the stratigraphic, and this has turned out to be of far greater significance than was expected and the only one which we shall here take up.

TYPICAL GRAPTOLITE SHALES

There are two graptolite areas in Europe which above all others have received the most careful attention of geologists and paleontologists: the first is that of southern Sweden and the second is the Moffatdale section in southern Scotland. The black shales in these two areas have been considered as the typical facies for these organisms, and have been cited by authors as the ones which most clearly point to the deep-water origin of the sediments. We shall therefore in the present discussion consider only these two sections, especially since more detail probably is known about them than about any other graptolite horizons in the world, and also because the senior author has made a special study of these regions in the field in Sweden under the guidance of Doctors Moberg and Wiman and in Scotland under the guidance of Doctor Benjamin Peach. We are not ready at present to say that the conclusions which we draw from the Lower Siluric of Sweden and south Scotland are necessarily applicable to all of the graptolite shales; but we shall be satisfied if we can offer convincing evidence that the two shale series which have been most unquestionably considered as deep-water deposits are really of near-shore origin. Before proceeding any further, it will be necessary clearly to define graptolite shales or *Graptolitenschiefer*. As currently understood, these comprise formations of variable thickness, in which bands of black carbonaceous shales, generally of slight thickness, alternate with gray shales and more or less frequently with arenaceous beds. The black shales usually contain the graptolites, sometimes in vast numbers, and with them rarely occur other marine organisms, chiefly inarticulate brachiopods; the gray shales, as a rule, are barren of fossils, though a scattered representation may occur. Formations rich in other marine organisms and containing in addition either sporadic graptolites or interbedded layers, with a concentration of the remains of these organisms, are *especially excluded from our present discussion.*

THE SWEDISH REGION

The areas to be looked at in detail provide us with two distinct lines of evidence. In Sweden, in the Lower Siluric, there was a steady advance of the sea northward over a land surface which had previously been subjected to erosion. During the advance there was a continuous overlap of the black shales on the eroded surface of the Ordovicic formations, the black shale zones rising in the geological scale as one goes northward. Thus we have here a progressive overlap, accompanying a positive movement of the strand-line, and the black shale facies advances with the advance of that line. In southern Scotland, on the other hand, we see the strand-line being gradually pushed seaward, not by any diastrophic movement, but by the encroachment of the continental deposits which fill up the littoral areas of deposition and force a retreat of the sea.

THE MOFFATDALE REGION

The Lower Siluric in the Moffatdale region consists of 98 feet of black and gray shales, the graptolites occurring in the thin black shale seams.

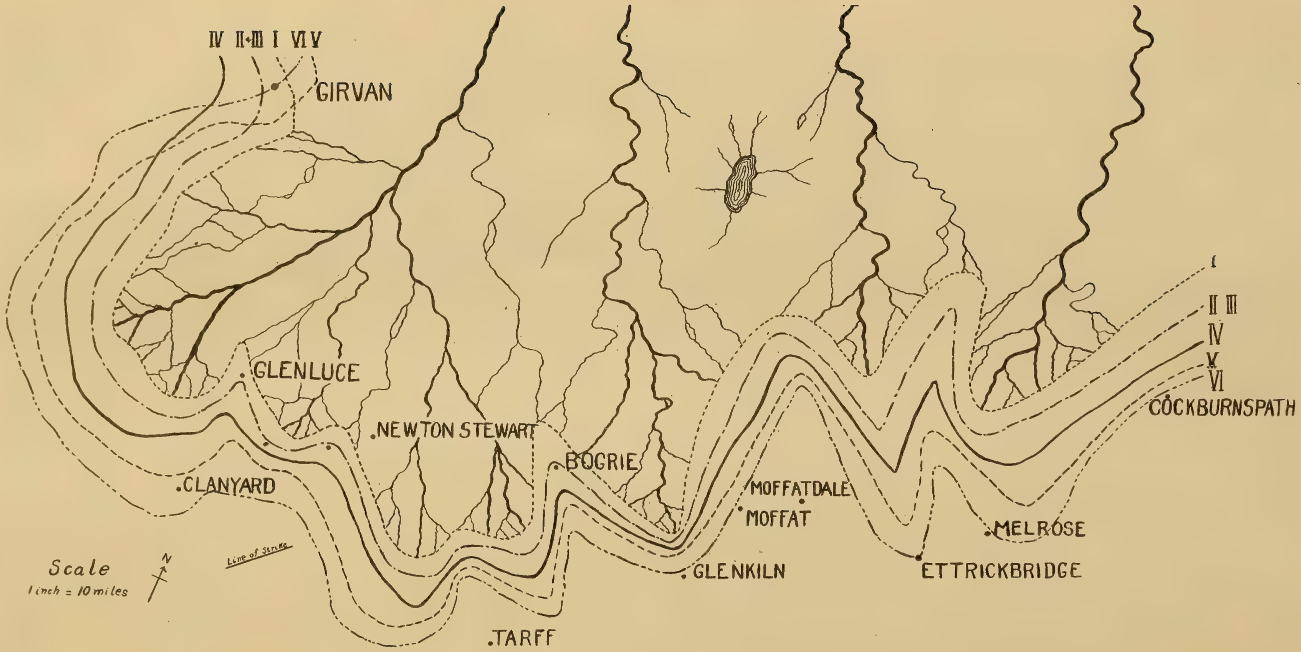
IV II-III I VI V
GIRVAN
GLENLUCE
NEWTON STEWART
CLANYARD
BOGRIE
MOFFATDALE
MOFFAT
MELROSE
ETTRICKBRIDGE
GLENKILN
TARFF
COCKBURNSPATH
I
II III
IV
V
VI
Line of Strike
N
Scale
1 inch = 10 miles

FIGURE 1.—*Diagram of the Birkhill Delta, in southern Scotland*

Each contour line represents the locus of the final occurrences of a single graptolite zone before it passes into unfossiliferous clastic deposits northwestward. The map has been enlarged twice at right angles to the strike in order to give approximately the conditions before folding; therefore it reads true for present positions only along the strike.

GRAPTOLITE ZONES

Lower Llandovery	Upper Birkhill	VI. Zone of *Rastrites maximus* V. Zone of *Monograptus spinigerus* IV. Zone of *Cephalograptus cometa*
	Lower Birkhill	III. Zone of *Monograptus gregarius* II. Zone of *Diplograptus vesiculosus* I. Zone of *Diplograptus acuminatus*

This one fact of occurrence alone is of the utmost significance, but may not here be dwelt on. In this Moffat series six distinct graptolite zones have been recognized, and they constitute the well known Birkhill divisions of the Llandovery. In making a series of detailed sections northwest-southeast across southern Scotland, it was soon found that there was a very regular transition of each black shale band northwestward into barren sandstones and grits, and it was especially interesting to note that as we traced any particular graptolite zone away from the Moffatdale region—east, north, or west—the black shale facies changed to a sandstone and grit and finally to a conglomerate, and that a concomitant of this change was the gradual disappearance of the graptolite fauna and the appearance of worm tracks, of various trails, and finally of eurypterid fragments, all clear indications of continental deposition by rivers. We have made a large number of sections across the southern belt of Scotland at right angles to the strike, and this is generally also approximately at right angles to the old shoreline. The same lithological and faunal replacement is seen in every section, the sequence holding so true to type indeed that one can predict with only small error or with none at all just what facies and what graptolites will occur at any given point, provided one already has two points located at the extremities of the section. The accompanying map has been made to show the actual migration of the strand-line southward; it is plotted to scale, and the different contour lines represent the last northward appearance of the graptolites in each zone before the shale passes northwestward into the barren grit and conglomerate facies. Allowance has been made for the folding which took place at the end of the Siluric and which involved all of these rocks, so that they now strike northeast-southwest. A measurement of the sections showed that they were foreshortened at least twice, so that in attempting to represent the conditions as they were during the time of deposition of the sediments it has been necessary to project all points twice their present geographical distance apart in a northwest-southeast direction. Thus the scale of the map is true for Lower Siluric time, but it is evident that the position of the various cities located on the map will show a distortion at right angles to the strike, all points being plotted twice as far apart in this direction as they are at present; the scale on the strike remains the same for the past as for the present. This careful plotting at once brings out the fact that Moffatdale, far from being in what was once a locus of deep-sea sedimentation, was as a matter of fact in the very center of a small bay or of a lagoon. We must indeed interpret the evidence as pointing to a deltaic origin of all of the sediments, for the black shales could not have been deposited under even normal near-shore marine conditions, else they would show a good representation of marine organisms, whereas they contain only graptolites. The grits into which the shales pass laterally must have been deposited wholly above sealevel, since they are devoid of all organic remains except worm tracks and the traces of fluviatile organisms.

CONCLUSIONS

From the two illustrations which we have cited we may draw the following conclusions: In the Swedish region, since the graptolite shale facies follows immediately, without even a sandstone facies, on an eroded land surface, the muds must have been deposited along shore and not even a few miles out to sea, since in every case there fails to appear any nearer shore facies than the black shales themselves. Moreover, the absence of a normal marine fauna, made up of members from several phyla at least, shows that the muds could not have been deposited in the deeper littoral portions of the sea, as claimed by many writers, because, so far as our knowledge allows us to judge, there is no portion of the littoral zone of the sea, be it near to or far from shore, that is devoid of an abundant and varied fauna consisting of many genera, species, and individuals from many classes of organisms. In southern Scotland we have a great torrential deposit, with a maximum thickness of 4,000 feet of conglomerates, grits, sandstones, and flags, passing into a black shale series which contains only one class of organic remains—the graptolites. We interpret these shales as mud deposits on the floodplain and in the lagoons of a large delta or series of deltas, where periodic high tides washed in the planktonic graptolites and stranded them on the flats, where they were quickly buried in the shifting muds. Occasionally the graptolites were swept far inland to regions where the distributaries of the delta were spreading out even coarser sediments, for at times the graptolites, much worn and broken, are found in the conglomerates, associated with worm tracks and eurypterid fragments. So far, then, as we may draw conclusions from a consideration of the two localities cited, it would seem that the graptolites which were holo- or epiplanktonic were buried in deposits more nearly of terrestrial than of marine origin.

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GEOLOGIC SIGNIFICANCE OF FOSSIL ROCK-BORING ANIMALS[1]

BY ALBERT L. BARROWS

(Presented before the Paleontological Society December 29, 1916)

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SIGNIFICANCE OF ROCK-BORERS DISTINGUISHED FROM BURROWERS IN MUD AND SAND

On seacoasts today, especially in tropic and temperate regions, animals are found boring into rocks which have been formed at various periods from recent to those of early geologic date. Related forms are frequently found as fossils in formations which are overlain by beds attributed to late Mesozoic or to Cenozoic times. The peculiar habitat of borers suggests that acquaintance with the conditions under which the recent forms live may offer distinct contributions to our knowledge of the depositional history of formations in which the fossilized forms are found. It is, however, of primary importance to be able to distinguish with certainty the special characters of each of the large number of marine animals which seek refuge in natural crevices or in holes, in order to be able to judge correctly the habits of fossils suspected of being rock-borers.

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[1] Manuscript received by the Secretary of the Geological Society April 30, 1917.

We must know particularly whether the holes in which these fossils may be found were made by the animals themselves or by other animals in firm or indurated rock or in compact sand, mud, or clay. Burrowers in mud or sand are found under a great variety of conditions, and the presence of these burrowers usually indicates a continuity rather than a cessation of deposition. The evidence offered by rock-borers, however, suggests the occurrence of a period of erosion between periods of deposition, and it is, therefore, with the true rock-borers and the characters which distinguish them from mud and sand burrowers that we are here especially concerned.

Borers into rock are found among all of the principal invertebrate phyla, and include sponges of the genus *Cliona*, several types of marine worms, sea-urchins, crustaceans, and mollusks.[2] Of this whole array of boring animals it is the fossil sea-urchins and certain pelecypod mollusks which are of especial significance, because the holes made by these animals are of a size not likely to be obscured, and because the pelecypod boring mollusks, at least, have occurred in abundance since Middle Mesozoic times.

ROCK-BORING SEA-URCHINS

Among the rock-dwelling sea-urchins but few boring species are known, and these belong largely to the genera *Echinus* and *Strongylocentrotus*. These sea-urchins are often found on the exposed parts of reefs where the waves beat with violence. It seems probable that the wash of the waves may at first have caused the ventral spines of the sea-urchins to have rasped away the rock to which the urchins clung, and that thus the capacity for eroding the rock might have been initiated quite accidentally, developing later into systematic movements on the part of the urchins, and finally resulting in the excavation of a hole and escape from the fury of the surf. Sea-urchins boring under such a stimulus are thus associated with definite conditions of exposure to the sea on a more or less open coast, with location at or near tide levels and attachment to hard reef rock. The bores of sea-urchins of the genus *Strongylocentrotus*, for instance, are large and cup-shaped, with openings but slightly smaller than the greatest diameter of the hole.

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[2] At the reading of this paper at the Albany meeting of the Paleontological Society, it was brought out in discussion that certain types of marine algæ are known to riddle limestone, and especially the calcareous shells of mollusks, with minute holes, and that certain worms are also frequent borers into rock. The writer regrets, however, not to be sufficiently familiar with the habits or characters of marine worms to be able to suggest a basis for distinguishing between those which may be regarded as habitual borers into indurated rock and those which construct slime tubes in beds of sand or mud.

ROCK-BORING PELECYPODS

The pelecypods which are known to bore only into rock fall into two groups: Mytilids of the genera *Adula* and *Lithodomus,* which probably use a solvent as the principal agent in boring, and pholads of such highly specialized genera as *Pholadidea* and *Parapholas,* which bore by grinding away the rocks with their shells. In addition to these there are other genera, species of which, exhibiting but slight morphologic differences, are known to burrow into sand or clay, to bore into rock, or to bore into both rock and sand or mud or clay. These include *Clavagella* and *Gastrochæna* of the Gastrochænidæ, *Platyodon* of the Myacidæ, and *Pholas* and *Zirphæa* of the Pholadidæ. Since these latter genera offer no marks by which it is possible to determine whether they may have bored only into mud, or at times also into mud, sand, or clay, fossils of these groups can not be relied upon to indicate the nature of the substratum into which they bored. All the true rock-borers seem to carefully select the rocks into which they enter, attacking readily limestone and shale and fine sandstones, even though bound by a strong cement, and avoiding conglomerates and the harder metamorphic rocks unless the latter are partially disintegrated by exposure. It is, of course, when boring into such sedimentary rocks as sandstone and shale, rather than into igneous rocks, that rock-borers can be of the greatest use in throwing light on obscure stratigraphic relations.

NESTLING PELECYPODS

In the study of the fossil rock-boring pelecypods the mode of origin of the boring habit and the method of boring throws certain light on the reliability of suspected rock-borers as determiners of the state of the substratum at the time when they lived. It seems probable that the waves may have caused the boring mytilids *Adula* and *Lithodomus,* members of a reef-dwelling group of pelecypods attached to the rock by means of a byssus, to grind out cavities, which may have become enlarged by solution of the rock due to the accumulation of acidic organic excretions. When nestling in natural crevices, these excretions may also have had a similar solvent effect in reshaping the cavity to fit the shell. Species of *Mytilus* living on exposed reefs illustrate today certain phases of just such a possible development of the boring habit. At all events, to judge from the shape of the holes of the mytilid borers, which conform accurately to the shape of the shells, it seems probable, though not yet demonstrated, that these borers do secrete a solvent effective either in dissolving the rock into which they bore, if limestone, or in dissolving the cement which holds the rock together, if shale or sandstone. Such an origin of the boring method in these genera, and the known association of mytilids with a rocky substratum rather than with sand or mud, mark these boring genera, when found preserved in bores, as having lived in a rocky substratum. They are not to be confused with mud- or sand-burrowers.

On the other hand, it is possible that the rock-boring pholads, using a mechanical method of boring by grinding the rock away with the hardened anterior edges of their shells, are derived from a type of mud- or sand-burrower, similar perhaps to *Panopea*, by a parallel development of the habit of boring, together with the necessary morphologic modifications. Borers derived in this way directly from mud- and sand-burrowers, which may have originally sought refuge from predacious enemies by burrowing, probably did not pass through a nestling stage, and they may be considered to have migrated under the process of development of the boring habit from beach or estuarine localities to reef localities nearer the open sea, where both a better food supply and a stronger and more permanent domicile might be obtained. The less specialized genera *Zirphæa* and *Pholas* illustrate just such a probable transition, and have not always been habitual borers into hard rock. The distribution of borers derived from sand-burrowing ancestors, both horizontally among the bays and inlets of the coast and vertically below tide level, is probably wider than that of borers derived from a reef-dwelling type.

CHARACTERISTICS OF ROCK-BORERS

The development of the habit of boring is, moreover, accompanied by certain morphologic modifications. Though the shells of the rock-boring mytilid species have no specialized processes by which the rock may be mechanically worn away, and show but few marks of shell erosion, the spindle-like shape of species of *Lithodomus* is characteristic of a borer and suggests the possible combination of mechanical and solvent methods in this case. Among the mechanical pelecypod borers, a shape presenting a superficial radial symmetry about the longitudinal axis of the bore is characteristic. Special development of the foot and valve muscles, the development of a myophore, and the production of a serrated edge with hardened grinding points on the anterior part of the shell occur in the pholads and are accentuated in the rock-boring species. Accessory plates may be added to take the place of a degenerated hinge apparatus. The subspherical shape of the anterior end of the shell is more pronounced in the rock-boring pholads than in those which may bore into sand or clay.

CHARACTERISTICS OF THE BORINGS

Features of the hole itself are often characteristic of the type of borer producing it and even positive proof that the borer entered the material when it was in a well advanced stage of induration. Thus the club-shaped bores, with very small openings made in the rock by the more highly specialized pholads, indicate a slow progress and enlargement with growth in hard material, in contradistinction to bores of more nearly uniform diameter, with rather large openings, made by species of *Zirphœa* in mud or clay. The shape of the bottom of the hole of sand- and mud-boring pholads is likely to be bluntly pointed rather than subspherical, as in the case of the rock-boring species of pholads. Sharp markings on the wall of the bore caused by the rasping of the points of the shell, as in the case of the holes of *Pholadidea*, also indicate that the hole was originally drilled into solid rock. The close conformation of the shape of a mytilid bore to the shape of the shell itself, without the deformation of the shell, fixes the responsibility for making the hole upon the mytilid.

INFLUENCE OF ENVIRONMENT

There is a definite correlation between the rock-boring habit and a location upon a more or less open coast where there may be ready access to a fresh supply of plankton food material fresh from the open sea and to water tolerably free from silt and of a proper salinity and oxygen content. These optimum conditions seem to be much more imperatively demanded by the rock-borers than by many of the mud- and sand-burrowers. In response to this correlation, we find the rock-borers usually absent from estuaries and embayments, where proper food can not be secured and where the deposition of silt may be heavy. Moreover, rocks and ledges which may be utilized by boring animals are found more frequently on the open coast than in embayments.

Unfortunately but little data is at hand concerning the depth in the sea at which boring animals may live. The plankton food supply extends to such a great depth as probably not to be a determining factor. Temperature is a very potent factor in limiting the distribution of marine animals, but would probably not be effective alone in limiting the range of rock-borers within 50 fathoms. Salinity remains nearly constant except near the outlets of rivers. Conditions of thorough aëration and the rapidly replenished food supply of the tidal zone seem to have attracted many animals of the littoral fauna, while the activity of the water at the surf line undoubtedly has been a factor in instigating the boring habit in the cases of the boring sea-urchins and mytilids. It seems probable that these types of borers will usually be found at no very great depth below the surface of the sea—that is, above 10 or 15 fathoms. These types as fossils may therefore be regarded as fairly close determiners of the approximate location of ancient coastlines.

Pholad borers, however, which are of a different derivation, may be found considerably deeper. Boulders of serpentine and of partially decomposed gabbro containing pholad borings and living pholads have been dredged in the Golden Gate, at the entrance to San Francisco Bay, from depths ranging between 33 and 50 fathoms. The geology of the Golden Gate makes it seem probable that these boulders were entered by the borers at or near the places where they were picked up. On the whole, it seems probable that even pholad borers will be found most abundantly under usual coastal conditions at depths ranging from the surface to only 25 or 30 fathoms, except in special places where the rocks are scoured bare by strong currents. Thus these fossils may also become indicators of the proximity of a former shoreline, but without the definiteness of the mytilid borers in this respect.

EVIDENCE FURNISHED BY ROCK-BORERS

In the presence of a violent change in the conditions of deposition over a given area, involving the laying down of hitherto absent sediments, the free-living fauna may readily move away. The sessile fauna may also be destroyed and washed away, and may leave but few remnants on the spot on which it once flourished; but the boring forms imprisoned within the rocky substratum must there remain, and may thus constitute the only relics of the former fauna indicative of conditions at this place at the time of inundation by the immediately overlying sediments. As a matter of field experience, fossil rock-borers are usually found at a contact between an old, more or less eroded surface and a bed of more recent material, where remains of the superficial fauna of the old surface rarely appear. The practical value of rock-borers as usually the only relics of the former fauna to be secured at the given horizon is, therefore, increased.

In two other respects rock-borers speak with definiteness: First, in differentiating absolutely between a suspected fault and a disconformity, and, secondly, in sometimes pointing with clearness to important disconformities which might otherwise be obscure. They may also be of use in confirming the exact location of a non-conformity between beds of differing inclination, though in such cases other indications of a non-conformity are usually apparent.

Evidence furnished by the Pelecypods

Evidence of a nature similar to that contributed by rock-borers may come from a group of animals which do not make holes of their own, but which, as nestlers, utilize the holes of other animals. This group includes barnacles, bryozoans, and several genera of pelecypods—*Tapes, Cumingia, Kellia, Diplodonta, Entodesma,* and *Mytilus,* when living in exposed localities. Few, if any, of the species of these genera are invariably nestlers; but it is when they are found in holes of other animals that they indicate that such holes must have been made in material sufficiently firm to serve both the original maker and a subsequent tenant.

There is also a group of pelecypods, including the genera *Saxicava* and *Petricola,* in which the habit of boring seems to be variable. Certain species of these genera have been reported to bore into "soft rock," often into clay banks and mudstones, and others have been found nestling in the holes of other borers. It seems probable that the same species may in certain localities bore into the softer rock structures, and in other localities satisfy its tendency for seclusion by becoming nestlers in the holes of other pelecypod borers. Since their present mode of living is so varied, but little confidence can be placed in these shells as indicating a definite state of the substratum in which they may be found, unless confirmed by evidence from other sources.

Conclusions

There are, then, certain sea-urchins of the genera *Echinus* and *Strongylocentrotus,* members of the pelecypod genera *Adula, Lithodomus, Pholadidea,* and *Parapholas,* which at present bore habitually into indurated rock and which do not enter less compact materials, liable to crumble or collapse. Fossils closely related to the known rock-borers, which probably use the solvent method and which are derived from reef-dwelling types, may be regarded with tolerable certainty as rock-borers when found fossilized *in situ.* Fossil borers derived from mud- and sand-burrowers are also to be regarded as habitual rock-borers if possessed of characters indicating a highly specialized boring apparatus, and probably have a wider range of distribution horizontally and vertically along the coast than borers of the former type. Morphologic modifications known to be associated with the rock-boring habit and certain characters of the holes in which the borers are found enable us to recognize certain rock-borers as such when fossilized. The occurrence of fossil nestling shells in the holes of borers is even better evidence of the induration of the rock at the time when the borers lived than the presence of the remains of the boring animals themselves. When found as fossils, therefore, both true rock-borers and nestlers indicate the existence of exposed hard rocks at the time when they were either covered by sediments or raised for a period out of the water, and there is evidence to suggest that these rocks entered by the borers were located in access to fresh ocean water, situated in the case of the echinoid and mytilid borers either at the sealevel or at no very great depth. Borers and nestlers may also be indicative of faults and disconformities, and may even constitute the only relics of the fauna of the region where they once lived.

In the history of deposition in a given locality, the full significance of the former existence of an exposed ledge of rock, as evidenced by the occurrence of fossil borers, must depend, however, upon information concerning the faunas of the beds in question and the sequence of faunas, both above and below, the texture of the rocks, their stratigraphic relations and correlation with other beds, and the recurrence of similar sets of conditions over a considerable range of territory.

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SECOND REPORT OF THE COMMITTEE ON THE NOMENCLATURE OF THE CRANIAL ELEMENTS IN THE PERMIAN TETRAPODA *

By WILLIAM K. GREGORY, *Secretary of the Committee*

WITH APPENDICES BY R. BROOM, D. M. S. WATSON, AND S. W. WILLISTON

(*Read before the Paleontological Society December 18, 1916*)

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INTRODUCTION

On June 29, 1915, Prof. H. F. Osborn requested Prof. S. W. Williston to act as chairman of a committee consisting of Messrs. S. W. Williston, E. C. Case, R. L. Moodie, D. M. S. Watson, and W. K. Gregory, the object of the committee being to consider and revise the names of the cranial elements of the earliest Tetrapoda. Dr. R. Broom was later appointed by the chairman. The committee has never been able to assemble and discuss the matter together, but each member has expressed his own views in correspondence with the Secretary and has had opportunity to consider the views of the other members of the committee. The first report of the committee was made by the Secretary at the Washington meeting of the Paleontological Society in December, 1915.

It is not yet possible to secure entire unanimity in the committee either as to the principles which must be followed in the adoption of names for the cranial elements or, in many cases, as to which term is to be preferred among several synonyms; and although substantial progress has been made toward this end, it is recognized that much further investigation and discovery is required in order to settle the difficult questions of homology between the various elements in amphibians, reptiles, and mammals, on which the final nomenclature must largely rest.

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* Manuscript received by the Secretary of the Geological Society April 30, 1917.

List of approved Names

The names approved and used by all members of the committee cover the majority of the cranial elements and are as follows:

- Angular
- Articular
- Basioccipital
- Basisphenoid
- Coronoid
- Dentary
- Ectopterygoid
- Epipterygoid
- Ethmoid
- Exoccipital
- Frontal
- Intercoronoid
- Interfrontal
- Intertemporal (see also sphenotic)
- Jugal
- Lacrimal (not lacrimal of Gaupp and von Huene)
- Maxilla
- Nasal
- Palatine
- Parietal
- Postfrontal
- Parasphenoid
- Postorbital
- Prearticular
- Precoronoid
- Prefrontal
- Premaxilla
- Prevomar
- Proötic
- Pterygoid
- Quadrate
- Quadratojugal
- Septomaxilla
- Stapes
- Squamosal
- Supratemporal
- Surangular (Supra-angular)
- Supraoccipital
- Tabular

List of Names as to which there is Divergence of Opinion

Names as to which there is some divergence in the committee, either of usage or of opinion as to homology, are as follows:

- "Alisphenoid" of reptiles.
  - Postoptic Cope (Williston).
  - Laterosphenoid (von Huene).
  - Otosphenoid (Broom).
- Dermosupraoccipital.
  - Prior term, used by Williston, Case, Gregory.
  - Postparietal Broom, Watson, Moodie.
  - Interparietal (when opposite pair are fused) Broom.

Epiotic (Miall) of crocodile.
Not "epiotic" of fishes (= tabular). See Watson's and Williston's remarks below.

Infradentary (Watson).
Anterior splenial of Broom.

Intertemporal, Williston, Case, Broom, Moodie, Gregory.
Watson believes a new name necessary, but provisionally uses intertemporal.

Opisthotic (see Paroccipital).
Paroccipital Owen, a prior term (Williston).

Petrosal of mammals.
Said to arise from four centers; commonly believed to represent fused proötic and opisthotic (or paroccipital).

Parasphenoid of authors.
Probably gave rise to mammalian vomer, as held by Broom; but practically all authors continue to use parasphenoid unless wishing to emphasize homology with mammalian vomer.

Postparietals, Broom, Watson, Moodie.
See dermosupraoccipitals (Miall).

Preangular, Broom.
Williston and Gregory are inclined to believe this is homologous with the true splenial of the crocodile.

Preparietal.
Recorded in many Therapsida, but not elsewhere.

Postoptic (see "alisphenoid").

Sphenethmoid.—The primitive brain-trough, as in the sturgeon and the frog. Later divides into orbitosphenoid and postoptic ("alisphenoid" of reptiles).

Splenial.—The typical splenial of the crocodile articulates with the angular, coronoid, surangular and dentary. The "splenial" of *Trimerorhachis* enters the symphysis and is separated from the angular by the "postsplenial" (see Watson and Williston below).

Supratemporal, the dorsal element, above the squamosal and lateral to the parietal.

Temporal of Ichthyosaurs, Cuvier (the lateral element, often called supratemporal, lateral to the quadrate-carrying squamosal).

APPENDIX A.—COMMENTS BY R. BROOM

While uniformity in the nomenclature of the cranial elements is desirable, it is quite impossible that it can come about till the homologies of the elements found in the different vertebrate types has been completely established, which will not be for many years.

In the meantime what I think ought rather to be aimed at is the use of terms which will give rise to no confusion and the gradual elimination of synonyms as homologies become unquestionably established.

While priority in naming an element should have considerable weight in the choice of the term finally agreed on, it is not advisable that it should be at all strictly adhered to, as in many cases it would result in needless confusion.

The suggestion made by Moodie that the B. N. A. terminology be adopted is, in my opinion, an unwise one. The bones of the human skull are in many cases complex, and to use the name which has been applied to a complex for a part of the complex in a lower form will give rise to hopeless confusion. For example, "maxilla" is the approved B. N. A. term for a bone which in the human subject bears incisors, canines, premolars, and molars. It is doubtless homologous with the premaxilla and maxilla of the lower forms, but not strictly homologous with either one, and if Moodie's suggestion were agreed to it would at once be necessary to rename the maxilla in the lower forms the "postmaxilla." Or, if the name maxilla is to be retained for only one part of the complex in the lower forms, why should not the name os temporale be applied to the squamosal in lower forms, or os sphenoidale to the basisphenoid, or os occipitale to the basioccipital?

The human anatomists have in the last two hundred years done singularly little toward the determination of the homologies of the cranial elements. Almost all the work has been done by the comparative anatomists and paleontologists. Some early human anatomist discovered the little bone in the ear called the incus, but it was the comparative anatomist that showed that it was homologous with the large "quadrate" bone which supports the jaw in most lower forms. And if the preservation of a name is to be in any way a complement to careful work, the comparative anatomist has at least a claim. In any case, I feel confident that the name "incus" will never be applied to the birds' quadrate. It would be much wiser if one term only is to be used to call the human incus the quadrate.

With regard to the majority of names approved by the majority of the committee I am in agreement. There are one or two concerning which I should like to make a note.

Dermo-supraoccipital.—This term of Miall's is approved by Williston, Case, Gregory, Moodie. Watson and I have used a term proposed by me in 1903—"postparietal." As, however, there is now no doubt that the element is the homologue of the mammalian "interparietal," there is no need for a new term at all. The interparietal has long been known in mammals and we can trace every step of it back to the Stegocephalian. Sometimes it is paired; sometimes single.

Ectopterygoid.—I have no objections at all to this term, though I have generally used the term "transpalatine."

Epipterygoid and *Alisphenoid.*[1]—I regard the reptilian epipterygoid as homologous with the mammalian alisphenoid, and if this is ultimately conclusively proven the name alisphenoid might quite well be applied to the reptilian element. In the Crocodilia, Aves, Dinosauria, and Ophidia there is an element which has usually been referred to as "alisphenoid," but which is probably not homologous with the mammalian "alisphenoid." This element is also met with in some Therapsida. Believing that it is not the Alisphenoid, I have [Croonian lecture, 1913 (1914)] named it otosphenoid.

Epiotic.—Concerning this bone I can say nothing. It certainly does not occur in the Therapsida nor in any group I am familiar with at first hand.

Interfrontal.—This name, first proposed by Watson, must, I think, be continued at present. It is not any part of the ethmoid, as I convinced myself by sections of the skull of *Eryops.* It is a pure membrane bone. The only doubt that arises is whether it may be homologous with the preparietal found in so many Therapsids. Not improbably the two elements are distinct.

Lacrimal and *Prefrontal.*—There is, I think, no question that the lower element is the mammalian lacrimal. It can be traced right back through the Therapsida to the Stegocephs.

Opisthotic or *Paroccipital.*—Till recently I used the former, as it seemed the term most generally used; but a couple of years ago I adopted the latter, as it seemed to have the better claim.

Preangular or *Postsplenial.*[2]—These two names are synonyms for the element which lies behind the first lower element in the Stegocephalian jaw. During August, 1913, I was working at the jaw of *Eryops* and *Trimerorhachis* in the American Museum and discovered a new element. On September 9 I posted to the Anatom. Anz. a paper describing the jaw and naming the element "preangular." During August, Professor Williston independently discovered the same element and had photographs taken of drawings, in which he named it "postsplenial." When my paper was posted, I had not seen Williston's photographs, nor was I aware that he was working at the Stegocephalian jaw. I first knew of Williston's discovery on the 24th or 25th of September, two weeks after my paper had been posted. That both Williston's drawing and mine were made quite independently will be manifest from the fact that each has some correct characters which the other omits. By the distribution of his photographs to various workers, certainly before the end of September, Williston's name of postplenial had at least some degree of publication a month before my paper appeared.

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[1] Compare Watson's views below, p. 980.—EDITOR.

[2] Compare Williston's remarks below, p. 986.—EDITOR.

Prearticular.—This term of Williston's has undoubted priority over goniale, and I fail to see any objection to it.

Prevomer.—This name was proposed by me for the "dumbbell-shaped bone" in *Ornithorhynchus* in 1895. This bone is certainly no part of the premaxilla in front or the vomer behind. It may be a neomorph or it may be, as I believe, the homologue of the paired "vomers" of the lower forms. It is unnecessary here to enter into the discussion. The matter may be regarded as still *sub judice.* The Cynodonts, which I thought would settle the question, are already too mammal-like. We must look to a slightly more primitive form for a settlement. In any case the mammalian prevomer is a distinct cranial element.

Splenial.[3]—The structure of the mandible in the Plesiosaur shows, I think, pretty conclusively that the anterior-inferior element, which forms part of the symphysis, is the homologue on the one hand of the anterior element in the Stegocephalian and Therapsid jaw and also of the splenial of the Crocodilian jaw.

Supratemporal, Suprasquamosal, Supramastoid.—I am quite willing to adopt any term agreed on by the majority. Suprasquamosal is not a new term of mine, having been used by Owen at least as early as 1859—certainly before supramastoid of Cope.

It is very desirable that some one should undertake a careful study of the ossification of the cranial elements in the human skull by modern methods. There is very much that yet remains unknown or obscure. For example, what are the sphenoidal conchæ (bones of Bertin)? In *Chrysochloris* I have discovered a pair of membrane bones probably homologous with these situated below the back part of the nasal capsules. Are they neomorphs? Again, in the most up-to-date text-book of human anatomy I have at hand, the petrosal is stated to be formed from four centers of ossification: 1, the opisthotic; 2, the proötic; 3, the pterotic, and 4, the epiotic, "often double." A little careful research would easily settle the homologies of these structures, and until it is done I fear some confusion will remain in the terminology of this region. If once we had a full knowledge of the human condition it will not be difficult to work down the vertebrate series.

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[3] Compare Williston's remarks below, p. 986.—EDITOR.

APPENDIX B.—COMMENTS BY D. M. S. WATSON

NOMENCLATURE OF SKULL ELEMENTS OF PERMIAN TETRAPODS

Principles.—Whenever possible, a bone is to bear the name which it has in the human skull under the B. N. A. list.

When a bone is not represented in the human skull, it is to be found in the crocodile and there named either after Cuvier or Owen, one or other of whose names will be in common use. When there is any doubt about the identification of a reptilian bone, it should not be called by a mammalian name. The most ineradicable errors are those which depend on the mixing of characters of two animals under one name, and to call the bone in the side of the brain-case of a crocodile alisphenoid deludes the unsophisticated student into believing that it is certainly homologous with the mammalian bone of that name. The use of a new term can *mislead* nobody. In other words, I object to Professor Williston's remark: "(I) am therefore disposed to retain the name alisphenoid until such time as it is certainly shown to be something else." Much prefer to substitute: "I refuse to call it alisphenoid until it is definitely shown to be homologous with the mammalian bone of that name."

Ethmoid.—Three bones are known which include ethmoid as part of their title:

1. The Mesethmoid.—This is a cartilage bone replacing the cartilaginous nasal septum in Mammalia.

2. The Ethmoturbinate.—A cartilage bone replacing the cartilaginous scrolls developed from the middle of the paries nasi in mammals.

3. The Sphenethmoid (W. K. Parker).—A cartilaginous ossification in the front half of the orbitotemporal region and the posterior parts of the planum antorbitale, septum, tectum, and solum nasi—only in frogs and toads. The "ethmoid" of Cæcilia is a general ossification of the whole anterior part of the cartilaginous skull, with many extensions into membrane.

From this it will appear that any bone which is to be called ethmoid (either plain or modified) must be a *cartilage* bone in the anterior part of the skull.

The Interfrontal and Internasal, terms of my invention, are dermal elements occurring not only in Stegocephalia, but in *Osteolepis* and *Dipterus*. Any section across the top of the head of *Eryops* will show that the interfrontal is quite distinct from the sphenethmoid, which lies below it.

The Internasal is equally a skin bone. They are to be distinguished from the similar-looking bones on the top of the head of some frogs and

Apoda, which I believe are real exposures of the sphenethmoid in the one and of the "ethmoid" in the other case.

Orbitosphenoid and *Alisphenoid.*—The orbitosphenoid of a mammal is a cartilage ossification in the ala orbitalis; the pair of ossifications either spread down into the lamina infra-cribrosa and through the basal plate of the orbitotemporal region or there is an independent center of ossification for the presphenoid in this region. In Monotremes the ala orbitalis lies entirely in advance of the optic nerves. In some types—for example, *Sus* and *Perameles*—the basal plate of the orbitotemporal region and the presphenoidal area is largely formed by the posterior end of the septum nasi. When this is the case, it is apparently obvious that the ala orbitalis is homologous with Gaupp's planum supraseptale of the lizard skull, which is connected with the tectum synoticum by the tænia marginalis, just as the ala orbitalis is by the commissura orbitoparietalis.

Professor Williston's lizard bone[4] was correctly described by Cuvier, who says that it is the only representation in lizards of the orbito- and alisphenoids of mammals. I do not yet know exactly how and when it ossifies, but it does seem to be a cartilage bone, perhaps ossifying in the bar separating the fenestræ metoptica and optica. If so, although analogous, it will not be homologous with the orbitosphenoid. As a matter of fact, there are usually three other calcifications in this region of the lizard skull—one in the septum, extending up to the brain-case, the others in the wall of the brain-case—but these are not apparently real bones. There is no evidence extant as to the mode of ossification of the "alisphenoid" of the crocodile, but I fancy from its relations it is probably homologous with Williston's lizard bone.

Bland Sutton many years ago showed that the cranial cavity of a mammal is not homologous with that of a lizard, because in the first case the Gasserian ganglion is inside the skull and in the other it lies outside, between the skull wall and the epipterygoid. Gaupp rediscovered this and called the space in which the ganglion lies in mammals the cavum epiptericum. In Monotremes there is a strong membrane separating this cavity from that for the brain—the tænia clinoorbitalis—and a cartilaginous nodule lying in front of the proötic notch, which I found in *Platypus*, lies in this membrane. It therefore follows that this membrane and its included cartilaginous elements is the original wall of the reptilian cranial cavity, with which it agrees in all relations, including the general distribution of nerve-exits.

Hence the mammalian alisphenoid can not be homologous with any ossification in the cranial wall of a reptile. In *Crocodilus* the Gasserian ganglion lies outside the cranial cavity in a small chamber, widely open back and front and included by the pterygoid and "alisphenoid." In Belodonts this cavity is exactly similar, but its outer wall is formed entirely by an epipterygoid.

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[4] Am. Jour. Anat., vol. x, p. 79.

Whether, as Oken (1811?), Parker, Baur (at one time), Broom, and Fuchs believe, the epipterygoid is homologous with the alisphenoid is much more doubtful. In my Monotreme skull paper, to be published very soon [Phil. Trans. Roy. Soc. London, ser. B, vol. 207, 1916, pp. 311-374, 3 pls.], I have gone into the question very fully, and concluded that the obvious reading adopted by these authorities is wrong in part.

The mammalian alisphenoid is an ossification of the ala temporalis, which spreads into the membranous cranial wall, which is not homologous with the cranial wall of lizards, but lies outside it. Gaupp has shown that part, at any rate, of the ala temporalis (great wing of the sphenoid of human anatomy) is homologous with the processus basipterygoideus of reptiles, amphibia, and fish. Broom shows that its outer end is homologous with the pars palatina of the palato-quadrate cartilage. Hence, from other reasoning to that above, the Crocodile "alisphenoid" can not be homologous with the true alisphenoid of a mammal.

Hence I accept v. Huene's name laterosphenoid for the "alisphenoid" of the Crocodile and all bones shown to be homologous with it.[5]

The skull of the living Amphibia differs from that of Reptiles in being extremely platybasic—that is, in having no interorbital septum—the lengthy brain-case extending forward to the nasal region and filling the whole space between the parasphenoid and the roof of the skull.

This condition in Amphibia is plainly secondary, depending on the dorso-ventral flattening of the head, which is a characteristic amphibian advance.

In the Carboniferous *Pteroplax* there is a large interorbital septum, which supports the anterior end of the brain-case, just as does the largely membranous interorbital septum of the lizards and teleosts. The gradual flattening of the skull in large Amphibia (even in, say, *Eryops* and *Capitosaurus*), together with some enlargement of the brain cavity, leads to the gradual loss of the interorbital septum, the whole brain-case being floored by the parasphenoid.

Hence the characteristic "os en ceinture" form of the frog's sphenethmoid depends on the actual shape of the skull, which is purely secondary, and in types with a distinct interorbital septum we should expect the sphenethmoid, which is a rather general ossification of the cartilages of the front of the brain-case and the back of the nasal capsule, to include a large ossification in the septum.

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[5] Compare Williston's remarks below, p. 985.—EDITOR.

This is my justification for styling the bone surrounding this anterior end of the brain in *Pariasaurus,* sphenethmoid.

The pair of small cartilage ossifications in the anterior part of the brain-case of Urodeles, commonly called orbitosphenoids, obviously correspond with the hinder part of the frog's sphenethmoid, and broadly with the alisphenoids of the crocodile and Professor Williston's lizard bone. It is impossible to be certain of a strict homology with either, on account of the very complete chondrification of the anterior part of the brain-case in Amphibia and the lack of knowledge of the site and mode of ossification of the reptilian bones. For similar reasons there can be no certainty in their identification with the true mammalian orbitosphenoids, although the two bones are homologous in a general sense.

Difficulty arises in the name to be applied to the ethmoid of the Dicynodonts. This bone is very similar in its relations to the sphenethmoid of *Pariasaurus,* and had perhaps best bear that name, but its lower septal part, which forms a great deal of it, is homologous with the "ethmoid" of *Diademodon,* itself homologous with the mesethmoid of a mammal.

Perhaps the best way is to use ethmoid as a general term for any cartilage ossification in the posterior part of the nasal and anterior cranial regions; to restrict sphenethmoid to bones which have ossified partly in the nasal capsule and partly in the brain-case; and to use mesethmoid for all ossifications of the nasal septum alone. A new term is then needed for the "orbitosphenoids" of Urodeles.

The *Preparietal* (E. T. Newton) of Dicynodonts and Gorgonopsids is a membrane bone distinct from the sphenethmoid, and must be recognized as a *nomen conservandum.*

Petrosal.—The name Petrosal comes from the "petrous portion of the temporal" of human anatomy, and really means that bone, less the tympanic and squamosal; it is, in fact, identical with the periotic.

If I understand rightly, Professor Williston wishes to use this as equivalent to Proötic in reptiles.[6] This usage seems to me undesirable for the following reasons:

The labyrinth of reptiles is included by three bones on each side: the paroccipital, which surrounds the posterior parts of the posterior vertical and horizontal semicircular canals and the posterior parts of the vestibule, sacculus, and lagena; the supraoccipital, which surrounds the upper parts of the anterior and posterior semicircular canals, and the proötic, which includes the anterior parts of the anterior vertical and horizontal semicircular canals and vestibule, sacculus, and lagena.

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[6] See Professor Williston's later comments below, p. 985.—EDITOR.

The mammalian petrosal surrounds the whole labyrinth.

In *Platypus* there are two ossifications known agreeing in all features with the proötic and paroccipital, and the supraoccipital does not include any part of the labyrinth. The Monotreme petrosal is plainly homologous with that of man, which hence includes the reptilian proötic and other things. The name petrosal can not, in consequence, be used for any reptilian bone.

Epiotic.—The Epiotic is said to be an element surrounding the upper parts of the vertical semicircular canals. W. K. Parker claimed to have seen it in *Crocodilus* and the chick. In the chick, Doctor Ridewood (B. M. N. H.), who spent some weeks looking for it, assures me it does not occur. I have never met anybody who could say that he had seen one. I am thus doubtful of its actual existence. On the other hand, it is not improbable that there really is an epiotic in *Pteroplax,* and I find that the supraoccipital of *Sphenodon* begins as a paired double perichondral ossification, so that it might be regarded as a fused pair of epiotics and not a supraoccipital formed in the tectum synoticum.

Septomaxilla.—This bone is a membrane ossification on the dorsal surface of the paraseptal (Jacobson's) cartilage; it hence has nothing to do with the Ethmoid, from which it is separate, even in *Siphhonops,* where the "Ethmoid" is most extensively ossified.

Postsplenial.[7]—The problem is, which of the two anterior infradentaries of the Amphibia (Stegoceph) jaw becomes the splenial of reptiles. The term infradentary has always been applied to all the elements of the angular-splenial row in Osteolepids, and it seems undesirable to now restrict it to any individual member of that row. Professor Williston's reasons for homologizing the "postsplenial" of Stegocephs with the splenial of reptiles is that in advance of that bone there is a small foramen (the anterior mandibular), which seems to agree with the foramen in the symphysis in advance of the splenial in reptiles. This argument is good, but Professor Williston has overlooked the fact that a precisely similar foramen in the symphysis in advance of this anterior element does occur in Amphibia, I believe in all Stegocephalia.

Hence there is just as much evidence in favor of the homology of the anterior bone in Stegocephs as the posterior, and I prefer to retain Splenial and Postsplenial.

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[7] See Williston's remarks below, p. 986.

Palate, Prevomer, Vomer, and Parasphenoid.—Vomer is by definition—that is, occurrence in man—an unpaired membrane bone lying below the basis cranii and stretching from the region of the pituitary to the region of Jacobson's cartilages. In man it arises as a pair of small elements below the nasal septum, with which a lot of other ossifications coalesce; in most mammals—for example, *Platypus, Perameles, Dasyurus, Talpa*—it arises by a single center under the posterior part of the nasal septum.

The lizard vomer and those of Crocodiles, *Sphenodon,* Frogs, Urodeles, and Cæcilia, arise as a pair of membrane bones surrounding the lower and mesial surfaces of the paraseptal cartilages, or what appear to be their homologues in the Amphibia. The single vomer of Chelonia arises from a pair of splints associated in the normal reptilian way with the paraseptals; it is hence different in origin to the vomer of mammals.

The parasphenoid of *Sphenodon, Crocodilus,* Urodeles, and Frogs is a membrane element arising in the ventral surface of the basis cranii in the hypophysial region, and running forward from here sometimes as far as the nasal region. In lizards this median splint fuses with a pair of small membrane ossifications lying below the basipterygoid processes and forming with them the Vidian foramina.

It will be seen that the mode of origin of the mammalian vomer is much more like that of the reptilian parasphenoid than that of the reptilian vomer.

Every one must admit that the classical view of the homologies of these bones is open to grave doubts. Their discussion takes a large part of recent paleontological and embryological literature, and to retain all three terms can not possibly lead to any confusion and reminds every one that the problem is still open.

The vomers of tortoises and birds are, of course, prevomers.

Supratemporal and Intertemporal.—With regard to the terms Supratemporal and Intertemporal I am quite willing to accept these on the score of current usage.

Dermosupraoccipital is a mouthful. Is it quite certain that Miall's bones in the Crocodile are really the right thing, and not perhaps scutes fused in?[8] I have never been able to see them, and can not at the moment get at his description. In any case, could we not shorten it to Dermoccipital, which is long enough?

However, if the rest of the committee are satisfied as to the identity of the bones I will gladly accept it, particularly as Miall's book on the Crocodile is an excellent one.

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[8] See Professor Williston's remarks below, p. 985.

Lower Jaw.—For the lower jaw I prefer Owen's terms for the bones: Dentary, Angular, Surangular, Coronoid, Splenial, with Prearticular, Postsplenial of Williston, and Pre- and Inter-coronoid.

APPENDIX C.—COMMENTS by S. W. WILLISTON

B. N. A.—I agree with Broom that a too close adherence to the B. N. A. will tend to retard the advance of comparative anatomy. I do urge, however, that wherever practicable the system should be followed, in order that we may have greater uniformity.

"Alisphenoid."—I have given no especial attention to the homology of the mammalian sphenoid bone in the reptiles. Inasmuch as those who have are more or less convinced that the so-called alisphenoid of the reptiles is not homologous with the "greater wing of the sphenoid," I am willing to adopt provisionally another name for the element. But why select "laterosphenoid" or "otosphenoid," when Cope long ago proposed the name "postoptic" for it?

Interparietal.—I can not accept the term interparietal,[9] because the term is misleading and false when applied to the early tetrapods. In all such forms known to me, the bone is not only paired, but *never* interparietal in position. To use a descriptive term that conveys an error is objectionable, as was justly urged against Jaekel's postnasal for adlacrimal.

Proötic.—The name proötic is in wide use (I have used it myself for years), and nothing will be lost by retaining it. I therefore reverse my vote.

Opisthotic.—I can not say the same for opisthotic. Since we must, I am sure, abandon epiotic for any reptilian or amphibian element, I can see no reason why Owen's original term, paroccipital, should be given up.

Prevomer.—I shall use the term prevomer for the paired and unpaired bones back of the premaxillæ in the Reptilia and Amphibia. I think, however, that their homologies are not yet satisfactorily solved.

Dermosupraoccipitals.—I have examined the dermosupraoccipitals in *Gavialis* and see no reason to doubt their cranial nature.[9]

Interorbital septum.—I can not accept Mr. Watson's statement that the absence of an interorbital septum in the modern Amphibia is secondary. "The lengthy brain-case extending forward to the nasal region and filling the whole space between the parasphenoid and the roof of the skull" is the condition in the early reptiles and temnospondyl amphibians of the Permocarboniferous of America.

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[9] Professor Williston has lately adopted "interparietals" instead of dermosupraoccipitals.—EDITOR.

"Epiotic."—I am glad to see that both Watson and Broom are skeptical about the epiotic of Huxley. I have long agreed with Baur[10] that there is no such bone in the reptilian skull.

"Anterior Splenial."—I am growing still more skeptical about the identity of the anterior splenial of the amphibians and *Pantylus* with the true splenial of crocodiles, but will so call it until there is more evidence. Is not Mr. Watson just a bit inconsistent in the face of his statement that "when there is doubt about the identification of a reptilian bone it should not be called by a mammalian name?" Unfortunately, the term presplenial has a sort of preoccupation, or I would suggest that the two bones in the amphibian mandible be called presplenial and postsplenial.

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[10] Journal of Morphology and Zoology. Anzeiger, 1889.

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